

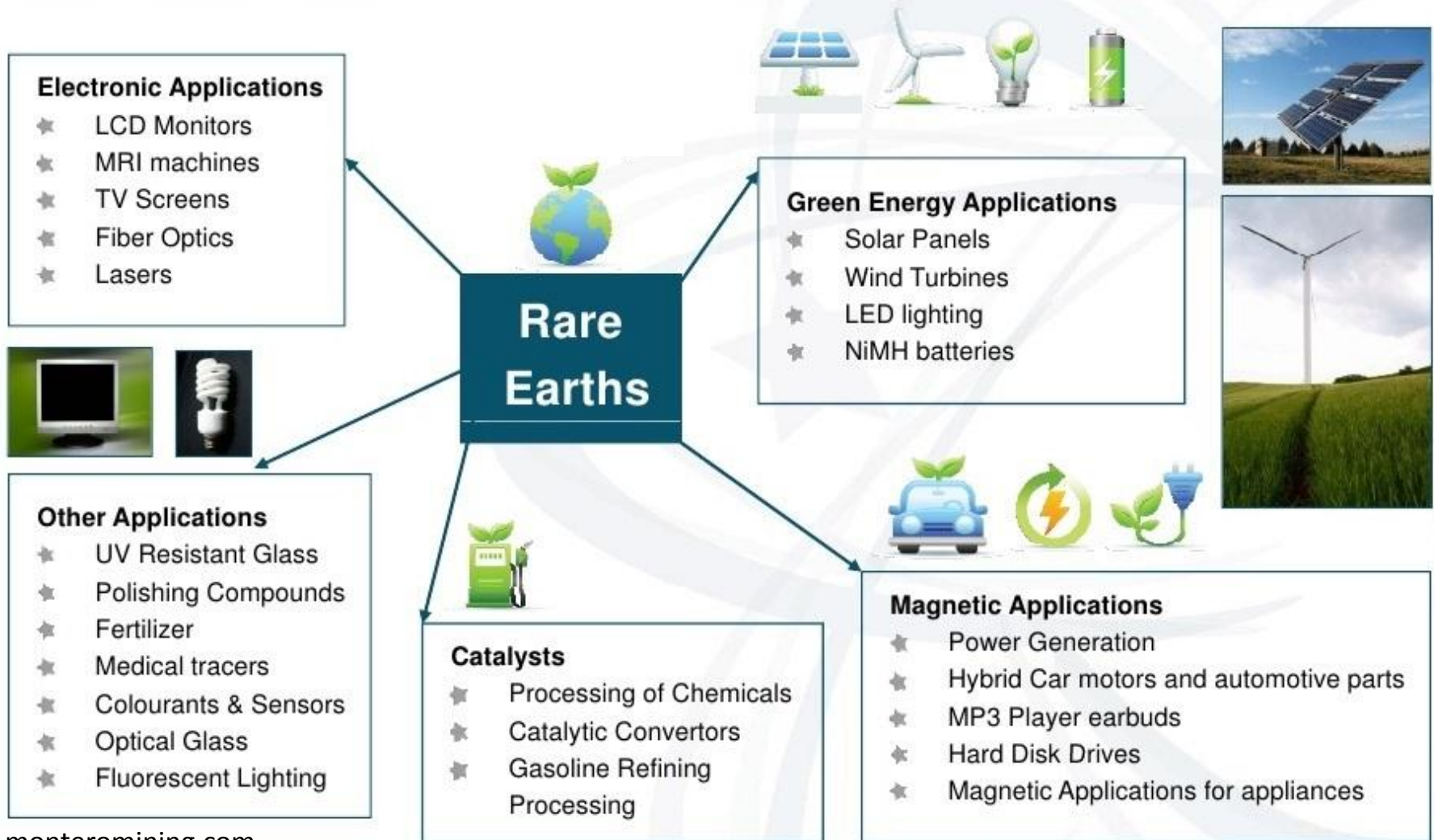
Characterization of Rare Earth Elements in WV Coal Measures

Jessica Moore

West Virginia Geological and Economic Survey



Rare Earth Elements: Essential Components of Modern Technology



Rare Metals in a smart phone



<http://www.outsiderclub.com/report/how-to-invest-in-rare-earth-metals-and-profit/1446>

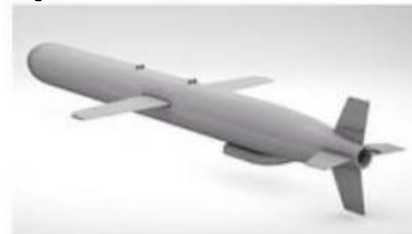
Homeland Security & Advanced Military Applications



Predator Drone
Neodymium, Samarium
Electric Motors and Guidance



Smart Bomb
Neodymium, Samarium
Electric Motors and Guidance



Tomahawk Cruise Missile
Neodymium, Samarium
Electric Motors and Guidance



Night Vision Goggles
Terbium, Erbium, Gadolinium
Optical Lenses



F-22 Fighter Jet
Europium, Yttrium Terbium, Erbium
Optical Systems, Visuals and Fiber Optics



Bullet Proof Vest
Yttrium
Hardened Ceramics



Bradley Tank
Yttrium
Hardened Ceramics



Radar Detection
Europium, Lutetium
Signal Amplification



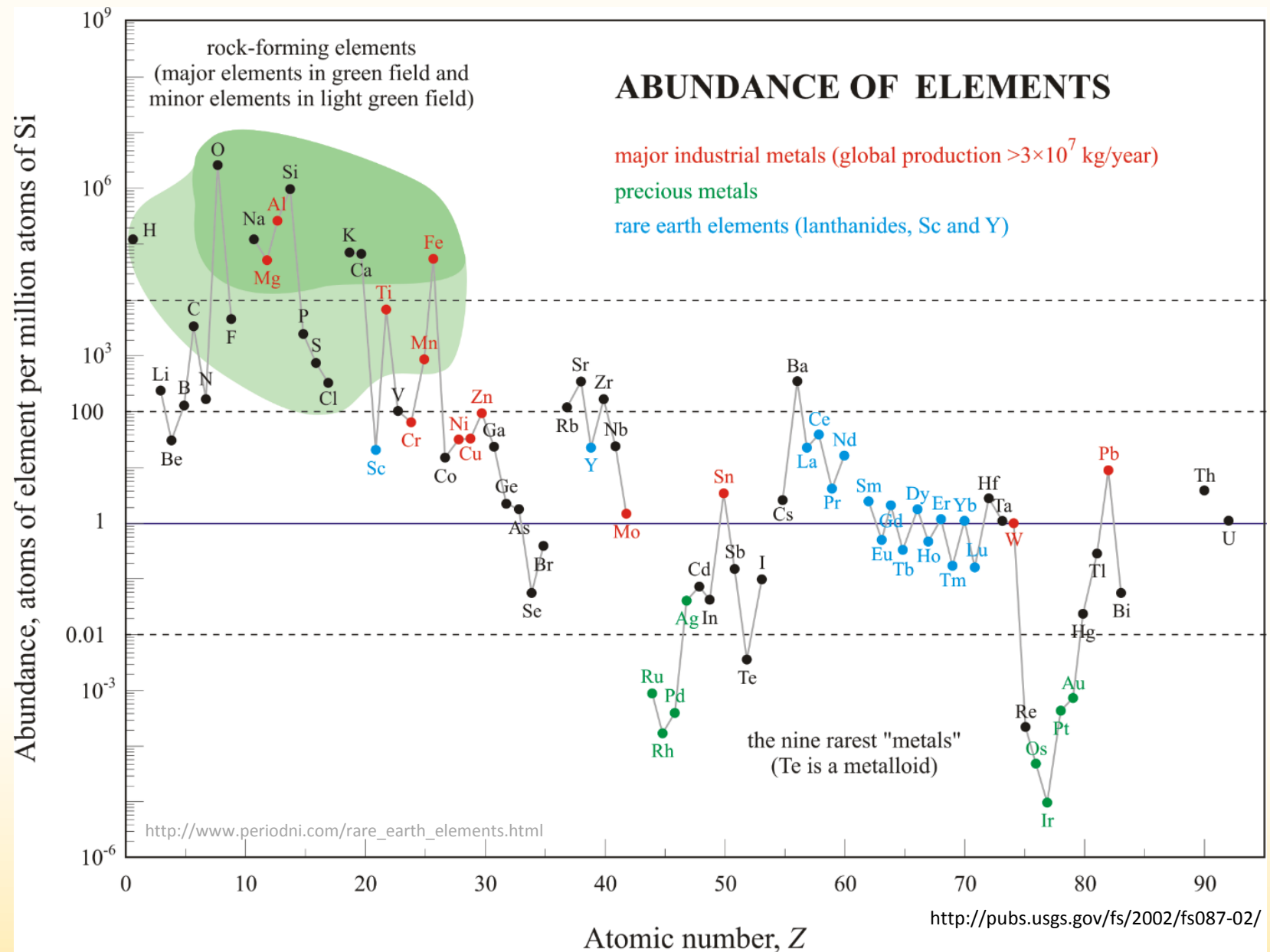
Nuclear Submarine
Europium, Lutetium
Sonar Detection

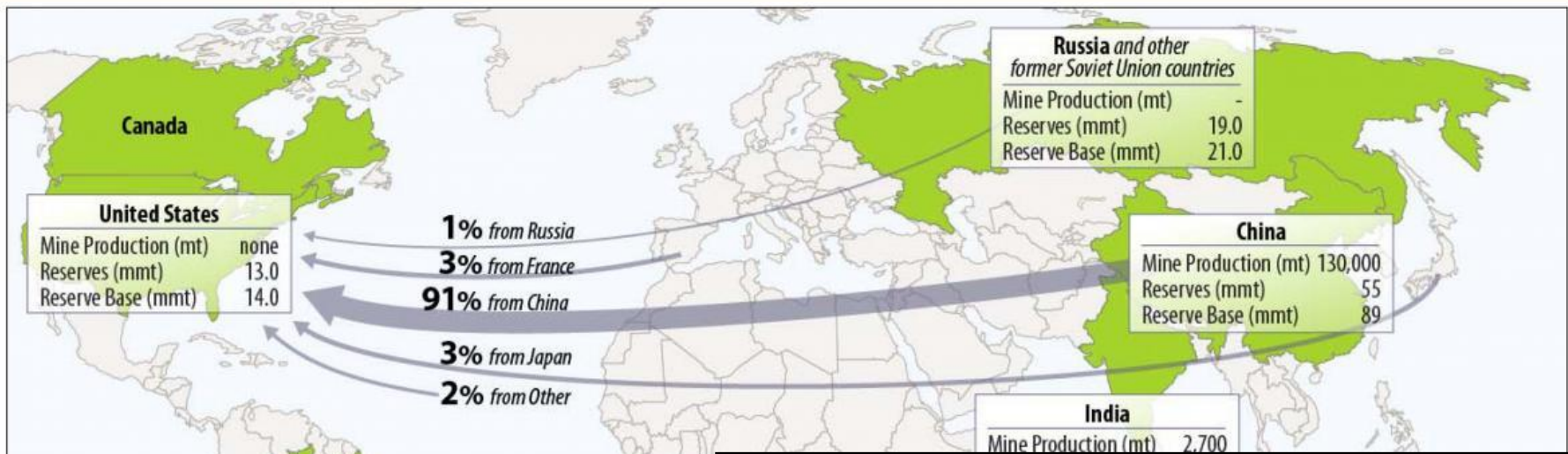
The Elements

The Elements

1 H Hydrogen																	2 He Helium				
3 Li Lithium	4 Be Beryllium															5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium															13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton				
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon				
57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium														
65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium															
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium							

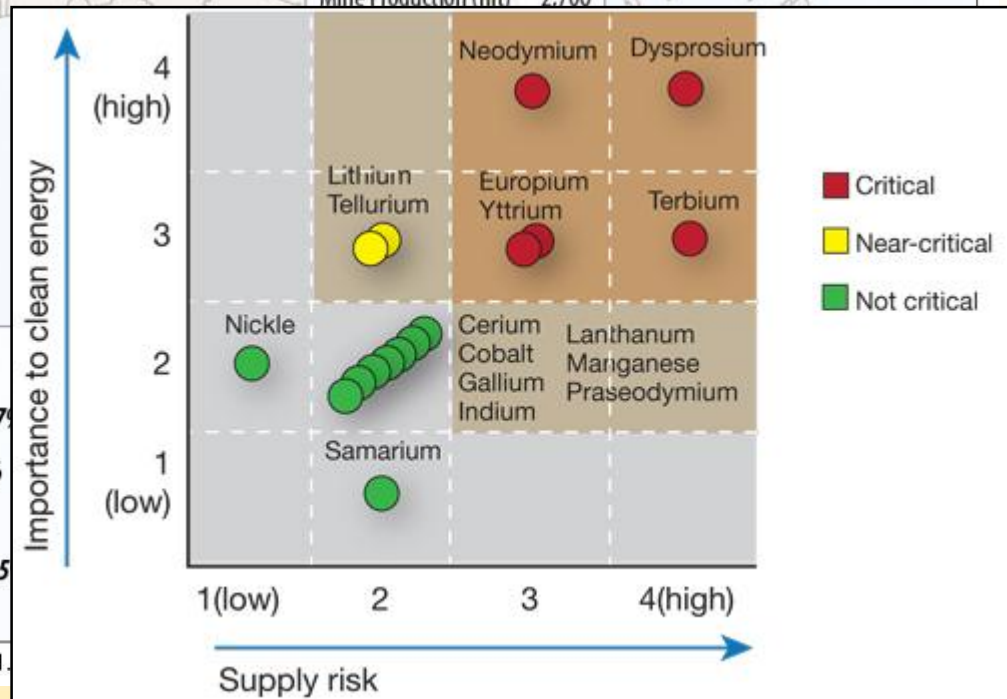
<http://sun-bin.blogspot.com/2010/10/rare-earth-elements-what-do-they-look.html>





<https://www.emaze.com/@AFOCCFTI/Plan-to-Reduce>

Source: U.S. Geological Survey, Mineral Commodity Summaries, 2008-2011.



<http://www.hybridcars.com/threat-rare-earths-shortages-hybrids-and-evs-remains-unclear-34571/>

West Virginia Governor's Energy Summit

October 6, 2016

Commodity Prices vary, but can be significant

RARE EARTH METALS

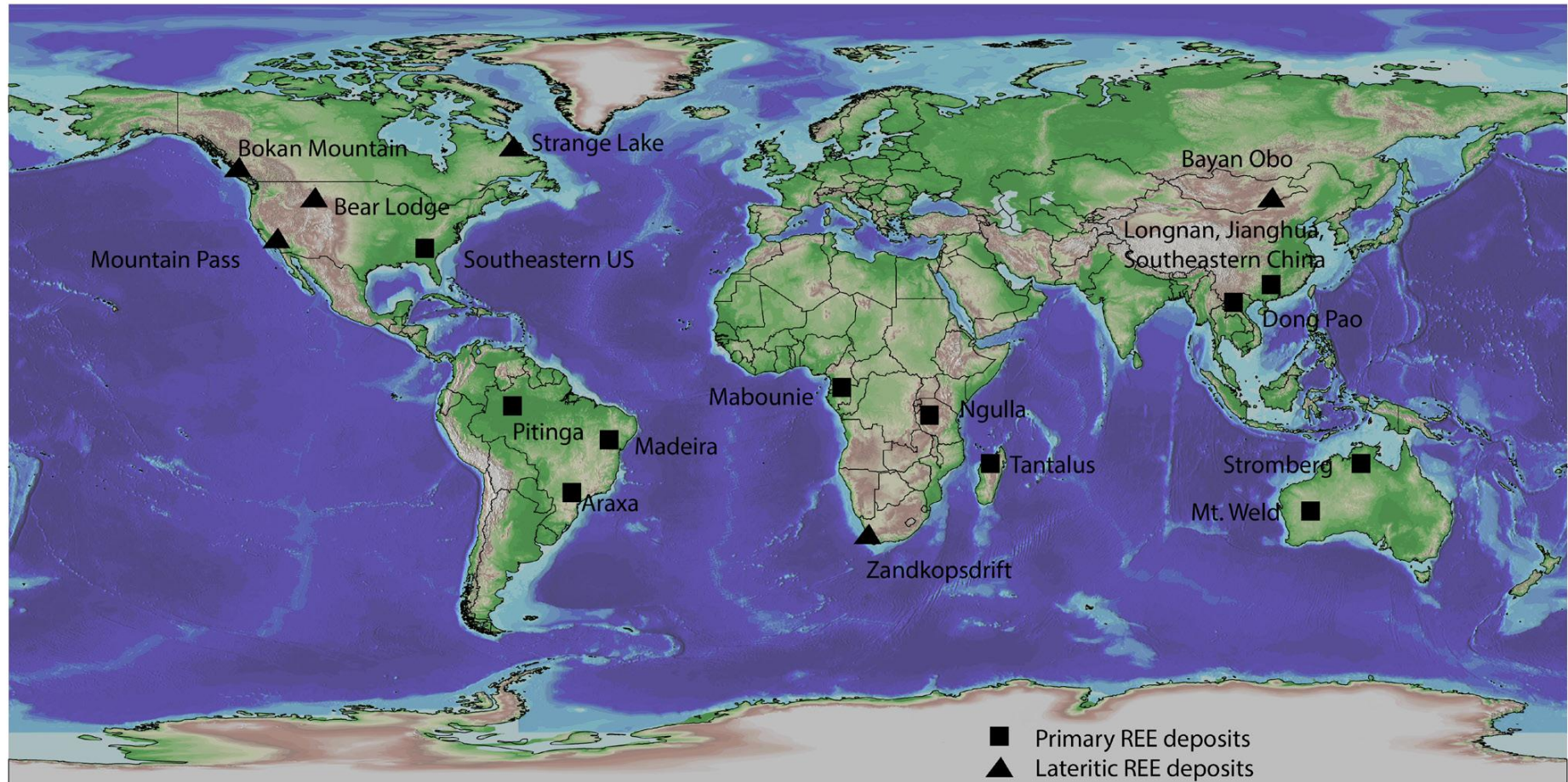


HEFA Rare Earth *Providing quality rare earth products and more*

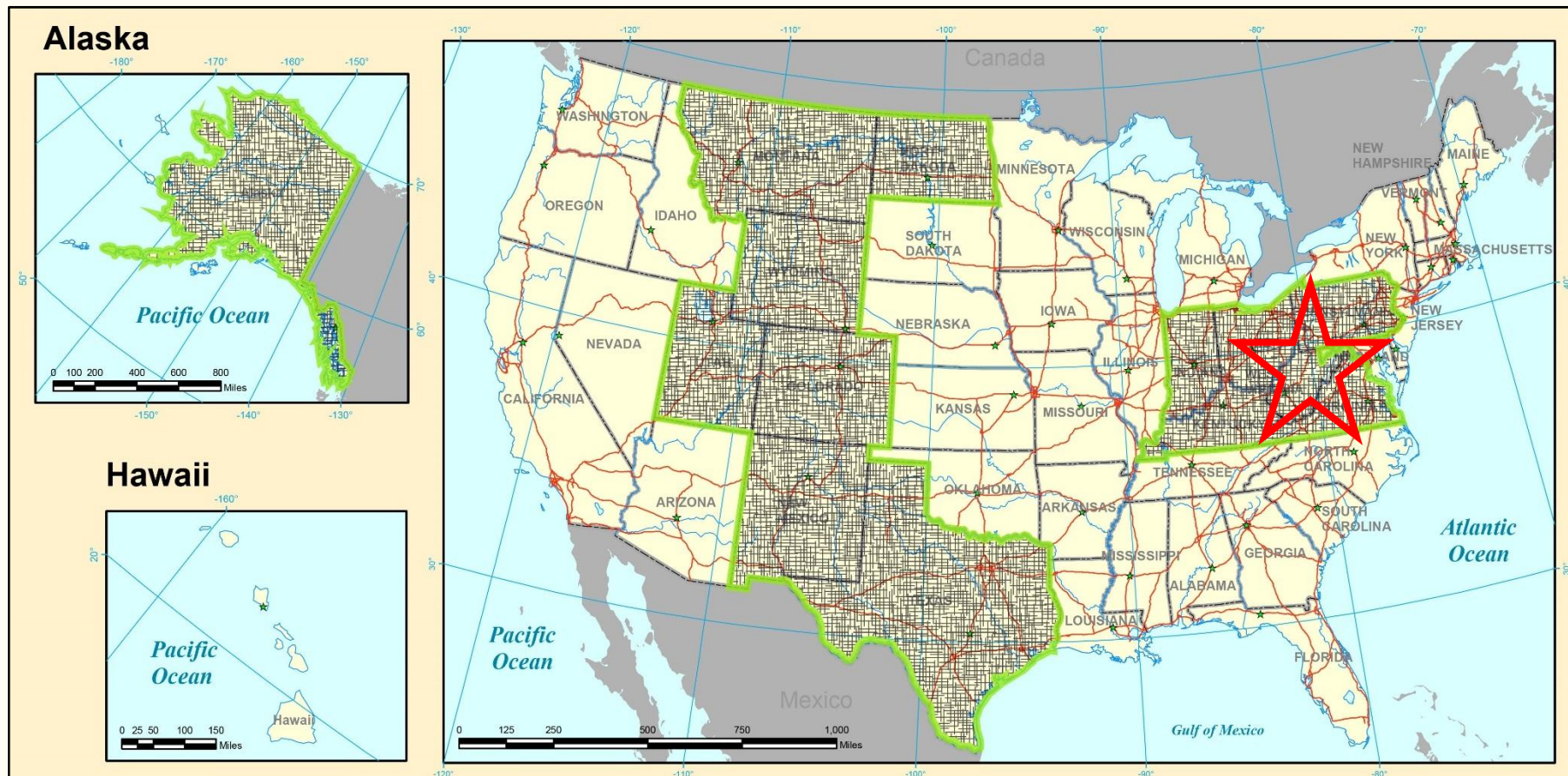
Source	Time	LIGHT RARE EARTH METALS		Last Price	% Week	% Year	31.Dec.2015	Units
mineralprices.com	05 Jul 2016	Lanthanum metal ≥ 99%	-3.0	7.00	-30.0%	-30.0%	10.00	US\$/kg
mineralprices.com	05 Jul 2016	Lanthanum Oxide ≥ 99.5%	-2.8	2.00	-58.3%	-58.3%	4.80	US\$/kg
mineralprices.com	05 Jul 2016	Cerium metal ≥ 99%	-3.0	7.00	-30.0%	-30.0%	10.00	US\$/kg
mineralprices.com	05 Jul 2016	Cerium Oxide ≥ 99.5%	-2.4	2.00	-54.5%	-54.5%	4.40	US\$/kg
mineralprices.com	05 Jul 2016	Praseodymium metal ≥ 99%	-90.0	85.00	-51.4%	-51.4%	175.00	US\$/kg
mineralprices.com	05 Jul 2016	Praseodymium Oxide ≥ 99.5%	-53.0	52.00	-50.5%	-50.5%	105.00	US\$/kg
mineralprices.com	05 Jul 2016	Neodymium metal ≥ 99.5%	-27.0	60.00	-31.0%	-31.0%	87.00	US\$/kg
mineralprices.com	05 Jul 2016	Neodymium Oxide ≥ 99.5%	-17.0	42.00	-28.8%	-28.8%	59.00	US\$/kg
mineralprices.com	05 Jul 2016	Samarium metal ≥ 99.9%	-13.0	7.00	-65.0%	-65.0%	20.00	US\$/kg
Source	Time	HEAVY RARE EARTH METALS		Last Price	% Week	% Year	31.Dec.2015	Units
mineralprices.com	05 Jul 2016	Europium Oxide ≥ 99.99%	-530.0	150.00	-77.9%	-77.9%	680.00	US\$/kg
mineralprices.com	05 Jul 2016	Gadolinium metal 99.9%	-40.0	55.00	-42.1%	-42.1%	95.00	US\$/kg
mineralprices.com	05 Jul 2016	Gadolinium Oxide ≥ 99.5%	-7.0	32.00	-17.9%	-17.9%	39.00	US\$/kg
mineralprices.com	05 Jul 2016	Terbium metal ≥ 99.9%	-260.0	550.00	-32.1%	-32.1%	810.00	US\$/kg
mineralprices.com	05 Jul 2016	Terbium Oxide ≥ 99.5%	-200.0	400.00	-33.3%	-33.3%	600.00	US\$/kg
mineralprices.com	05 Jul 2016	Dysprosium metal ≥ 99%	-120.0	350.00	-25.5%	-25.5%	470.00	US\$/kg
mineralprices.com	05 Jul 2016	Dysprosium Oxide ≥ 99.5%	-110.0	230.00	-32.4%	-32.4%	340.00	US\$/kg
mineralprices.com	05 Jul 2016	Erbium metal ≥ 99.9%	-70.0	95.00	-42.4%	-42.4%	165.00	US\$/kg
mineralprices.com	05 Jul 2016	Erbium Oxide ≥ 99.5%	-43.0	34.00	-55.8%	-55.8%	77.00	US\$/kg
mineralprices.com	05 Jul 2016	Yttrium metal ≥ 99.9%	-42.0	35.00	-54.5%	-54.5%	77.00	US\$/kg
mineralprices.com	05 Jul 2016	Yttrium Oxide ≥ 99.99%	-9.0	6.00	-60.0%	-60.0%	15.00	US\$/kg
mineralprices.com	05 Jul 2016	Scandium metal 99.9%	-3000.0	15,000.00	-16.7%	-16.7%	18,000.00	US\$/kg
mineralprices.com	05 Jul 2016	Scandium Oxide ≥ 99.95%	-3000.0	4,200.00	-41.7%	-41.7%	7,200.00	US\$/kg
mineralprices.com	05 Jul 2016	Mischmetal ≥ 99%	-2.0	6.00	-25.0%	-25.0%	8.00	US\$/kg

<http://www.baotou-rareearth.com/>

Resources distributed between two main types of deposits: Primary Ores and Lateritic Soils/Paleosols



http://repository.azgs.az.gov/sites/default/files/dlio/files/nid1570/ree_cocker_chp4.pdf



<https://www.netl.doe.gov/research/coal/rare-earth-elements>

U.S. Department of Energy analyzed hundreds of coal and coal by-product samples and found highest rare-earth assays in the northern Appalachian region

RARE EARTH ELEMENTS

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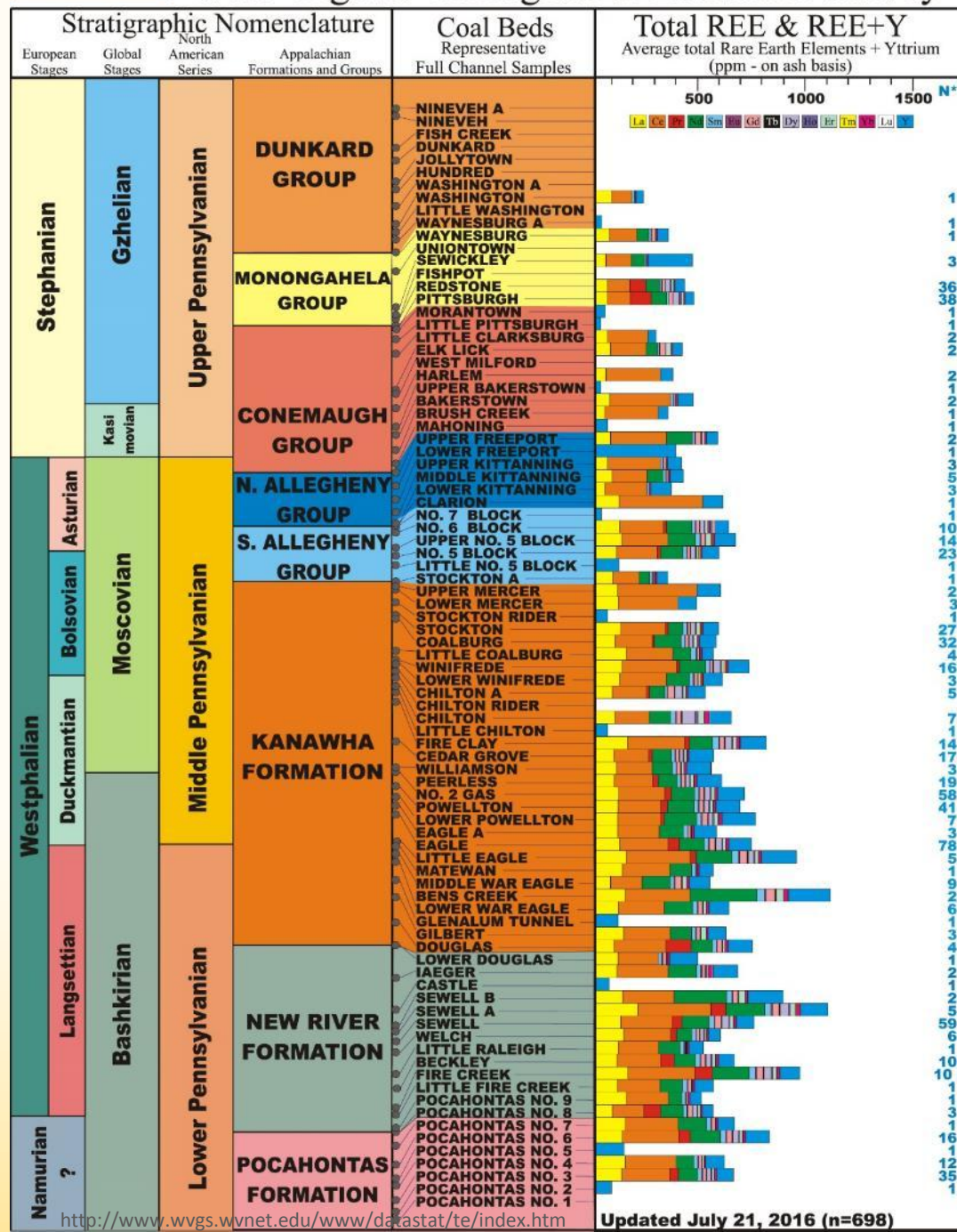
RARE EARTH ELEMENTS FROM COAL AND COAL BY-PRODUCTS

Comprising 17 elements from the periodic table, the group known as rare earth elements (REEs) provide significant value to our national security, energy independence, environmental future, and economic growth. REEs are important elements used in high-technology products such as catalysts, cell phones, hard drives, hybrid engines, lasers, magnets, medical devices, televisions, and other applications. The development of an economically competitive domestic supply of REEs will help to maintain our nation's economic growth and national security.



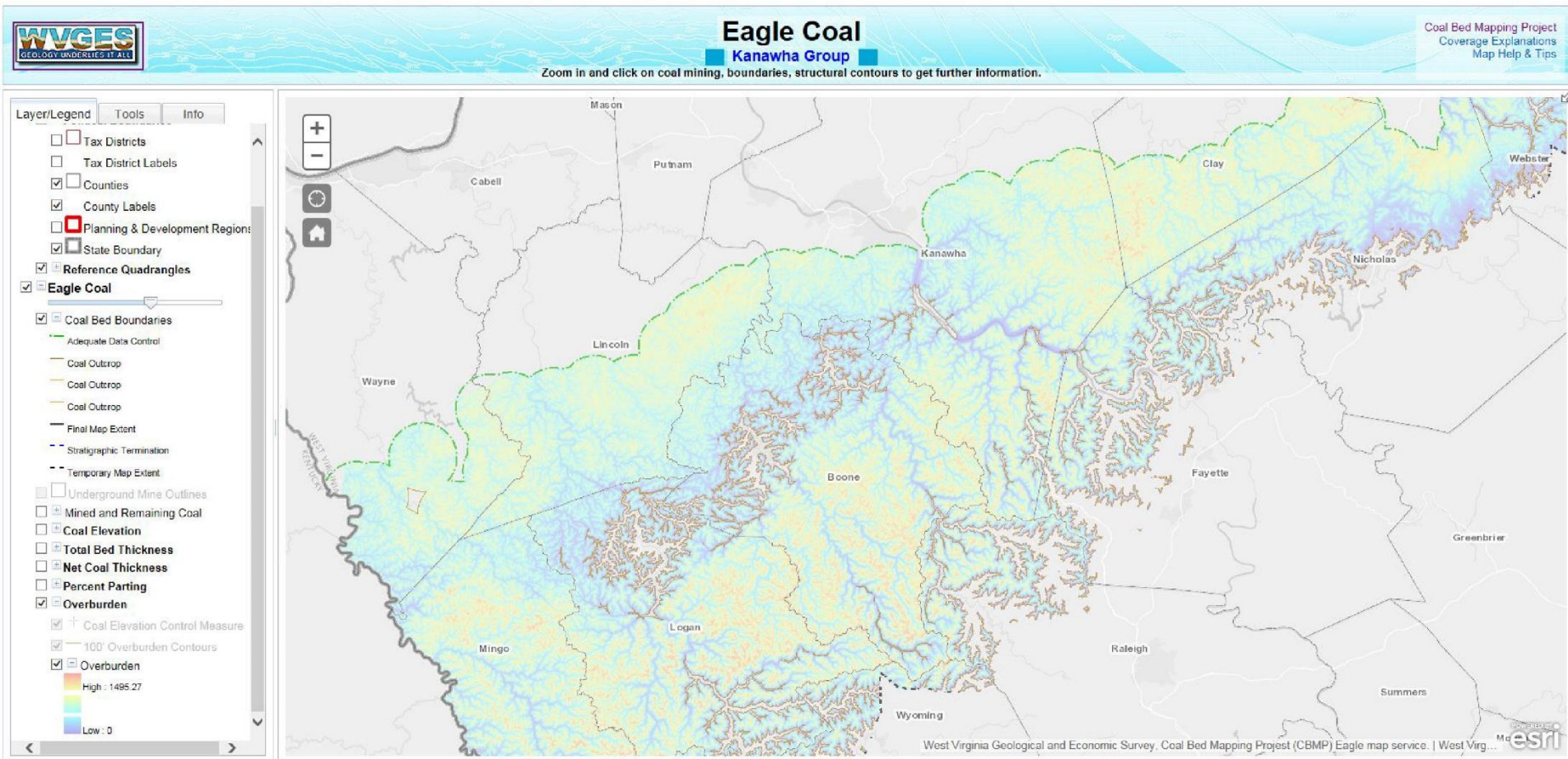
<https://www.netl.doe.gov/research/coal/rare-earth-elements>

West Virginia Geological & Economic Survey



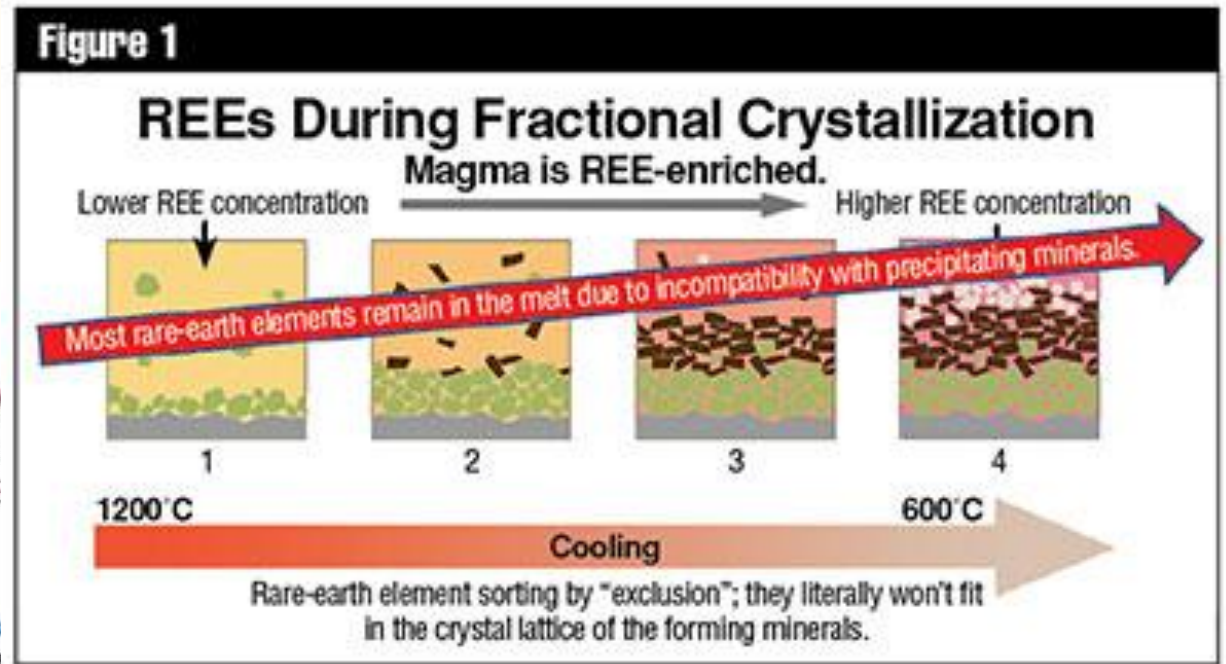
Updated July 21, 2016 (n=698)

WVGES Coal Program Interactive Mapping Application: Decades of Coal Research and Field Study



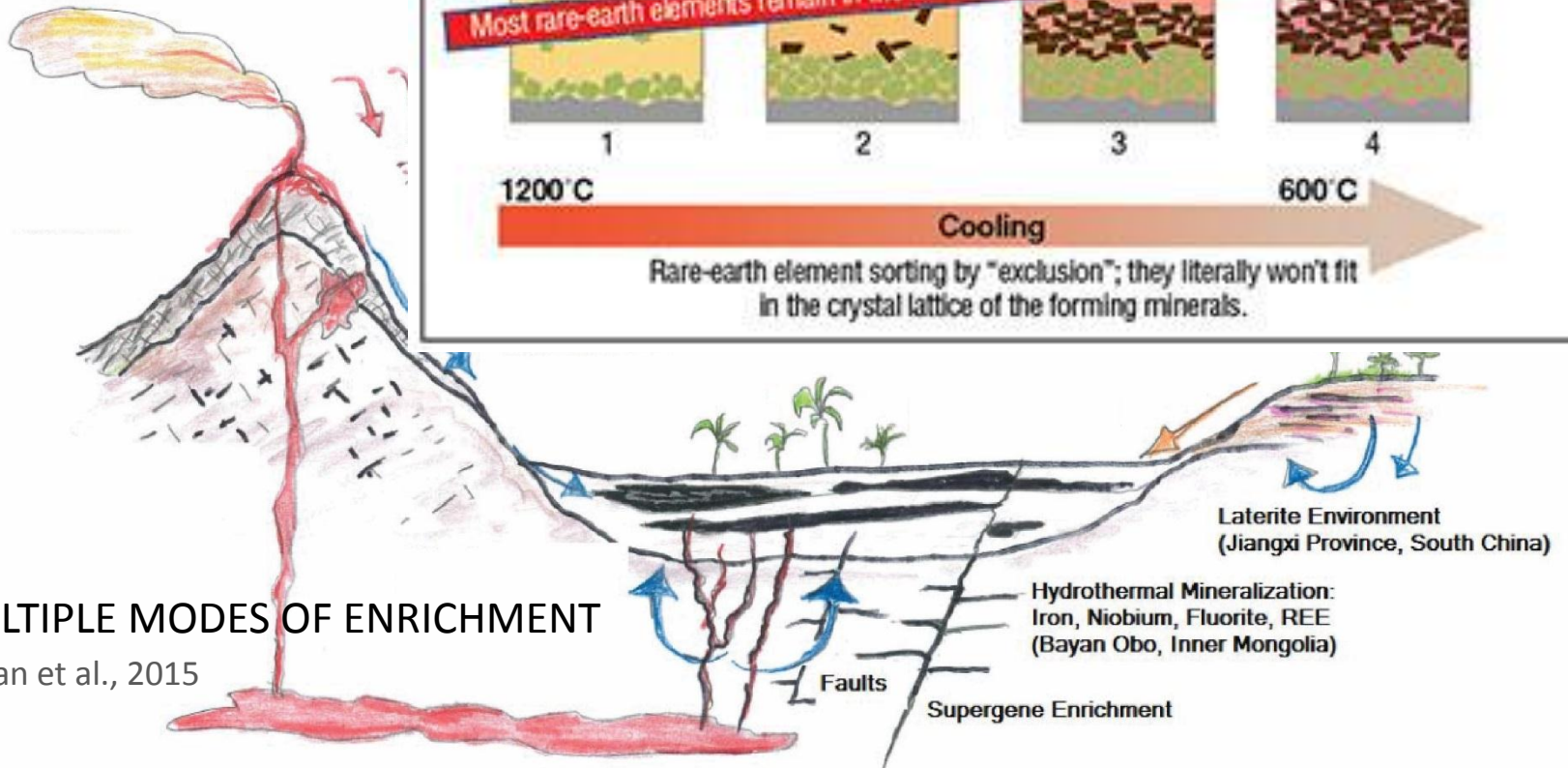
<http://www.wvgs.wvnet.edu/www/coal/cbmp/coalims.html>

Challenge 1: Identify Prime Feedstocks



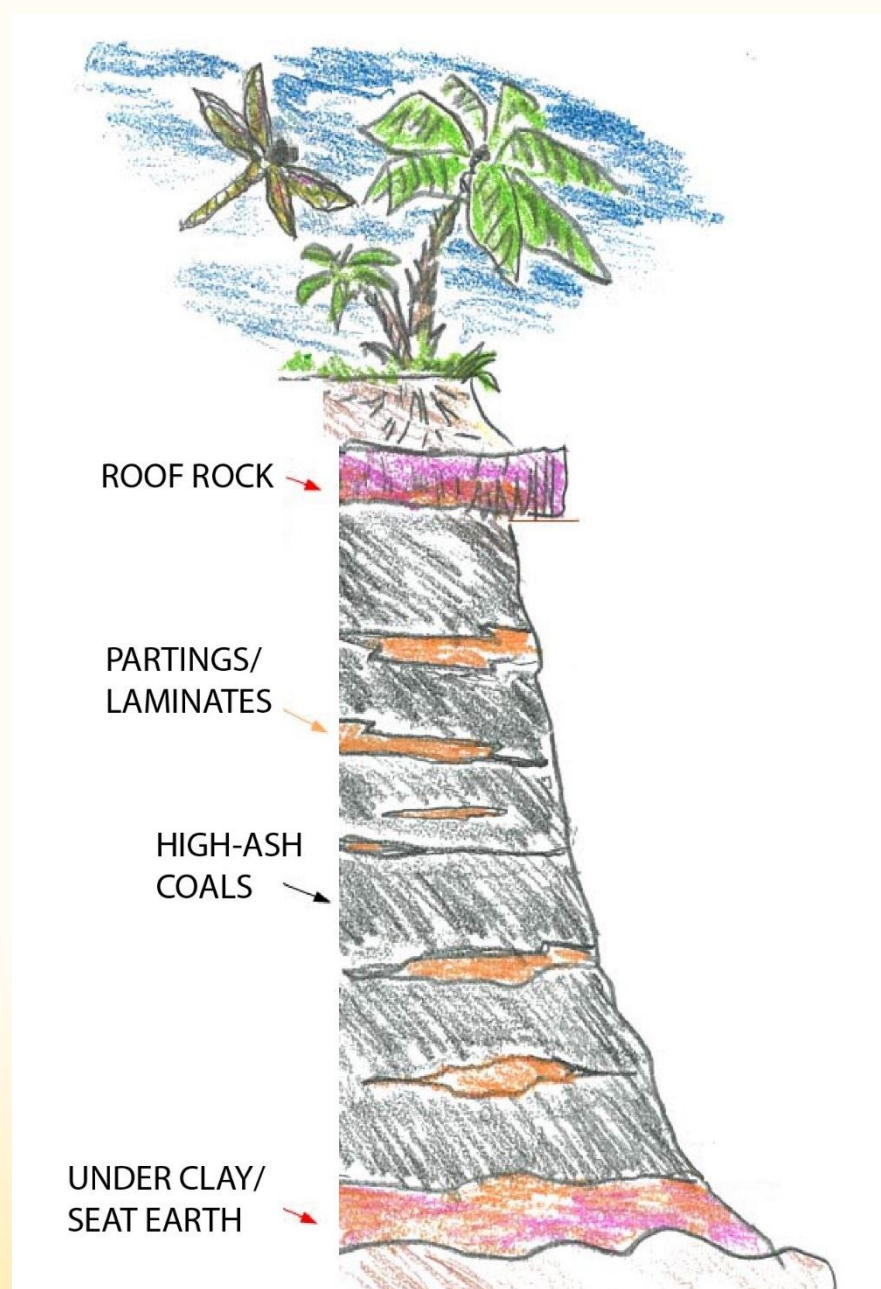
MULTIPLE MODES OF ENRICHMENT

Bryan et al., 2015



Multiple Enrichment Modes: several possibilities for concentration within coal measures

Bryan et al., 2015



Enrichment in Roof Rock and Underclay: Lower Kittanning, Clarion Co. PA

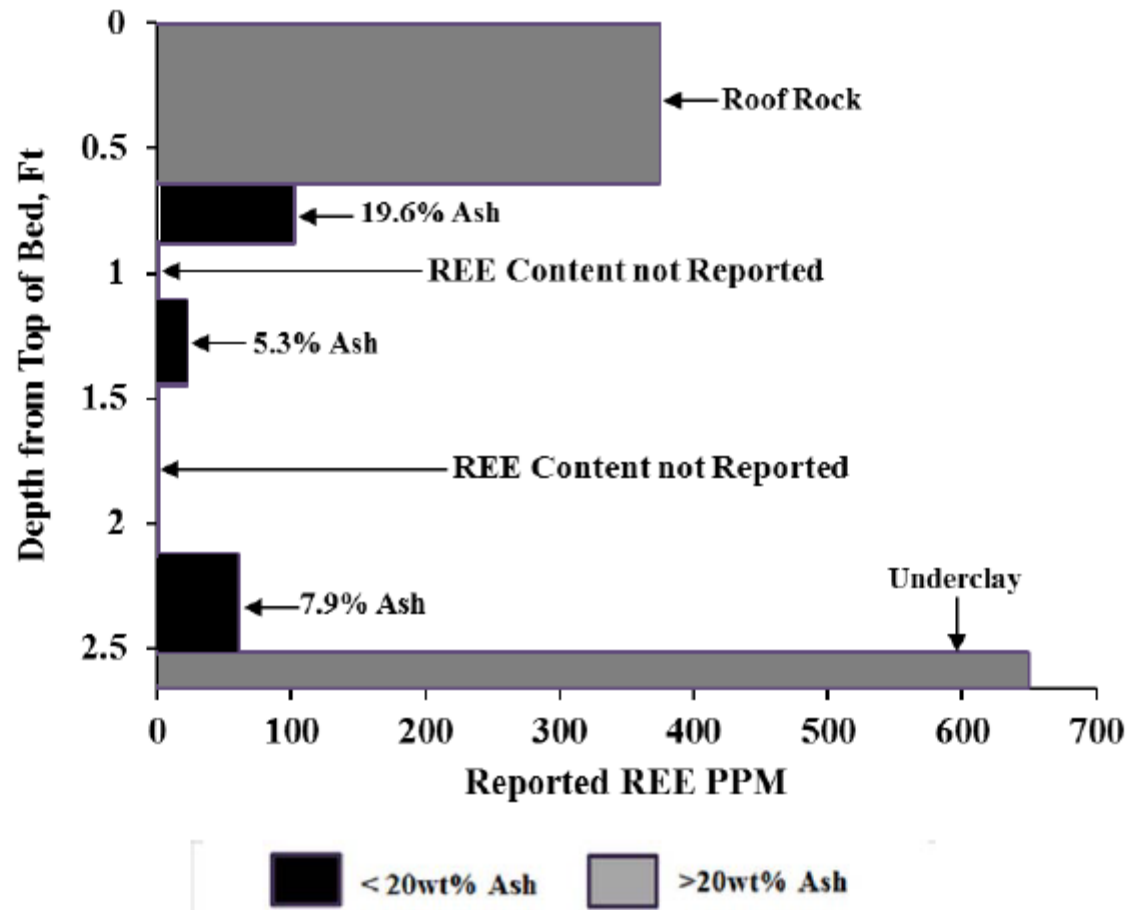


Figure 18: Stratigraphic Distribution of REE Content, Lower Kittanning Bed, Clarion County, Pennsylvania, Data from Schatzel and Stewart⁴².

Bryan et al., 2015

Enrichment in High-Ash Coals: Fire Clay Coal Bed, Letcher Co., KY

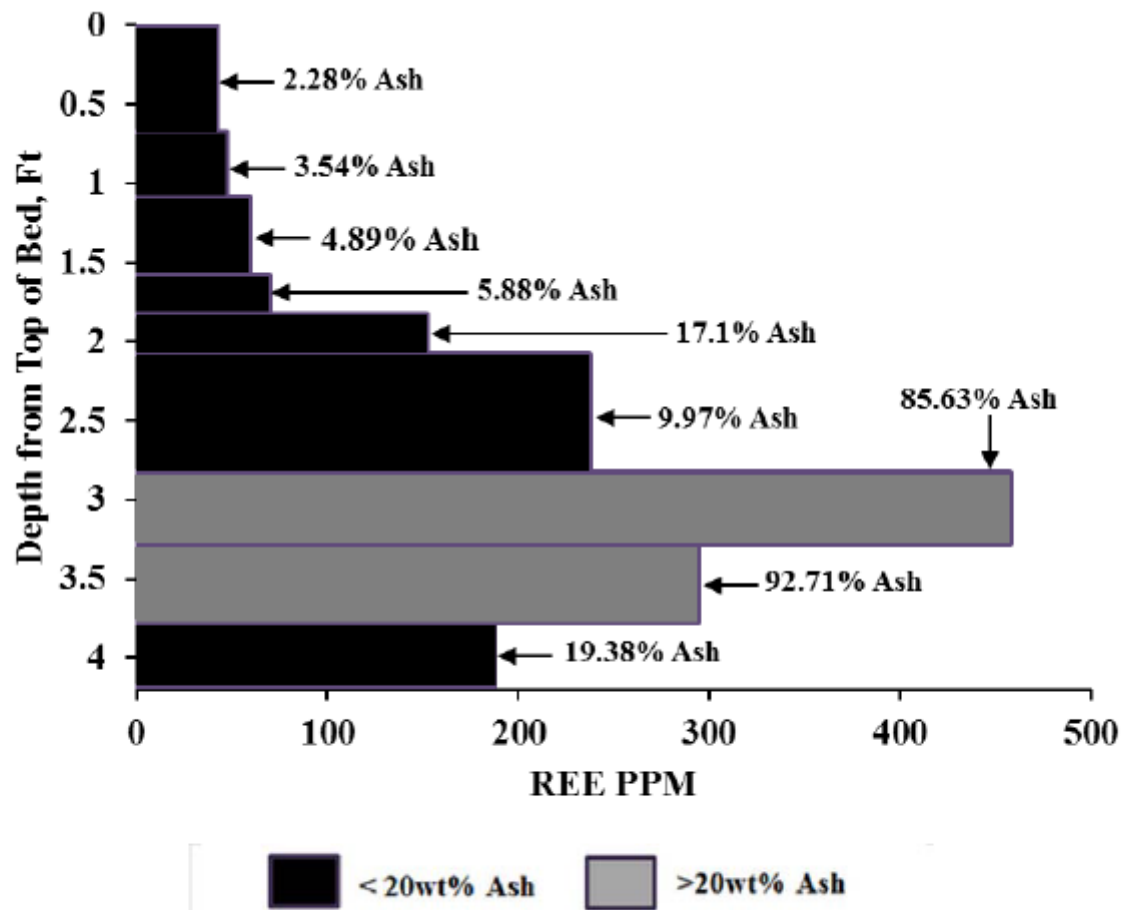
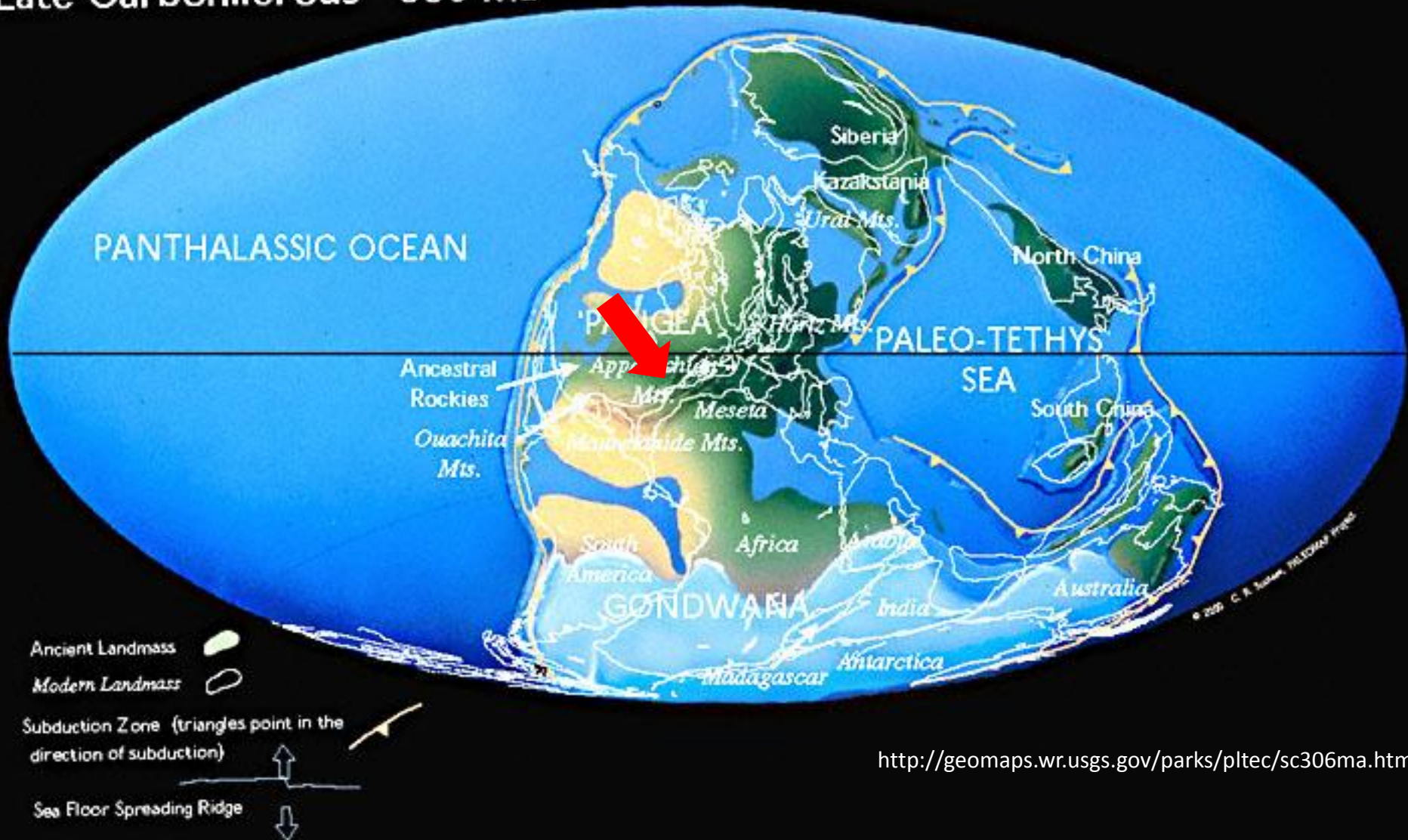


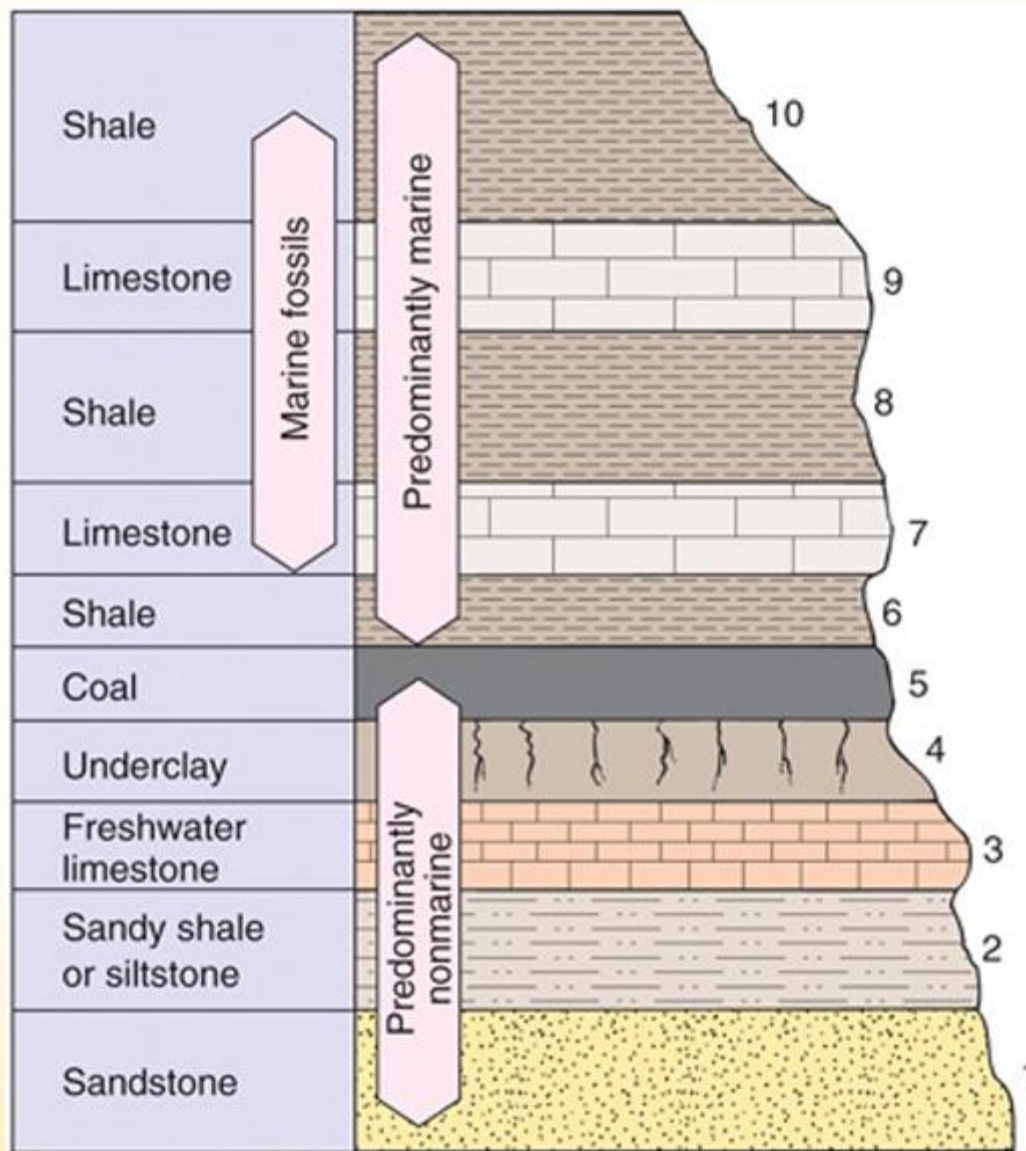
Figure 15: Stratigraphic Distribution of REE Content, Fire Clay Coal Bed, Letcher County, Kentucky, Data from Hower et al.⁵⁶

Bryan et al., 2015

Late Carboniferous 306 Ma

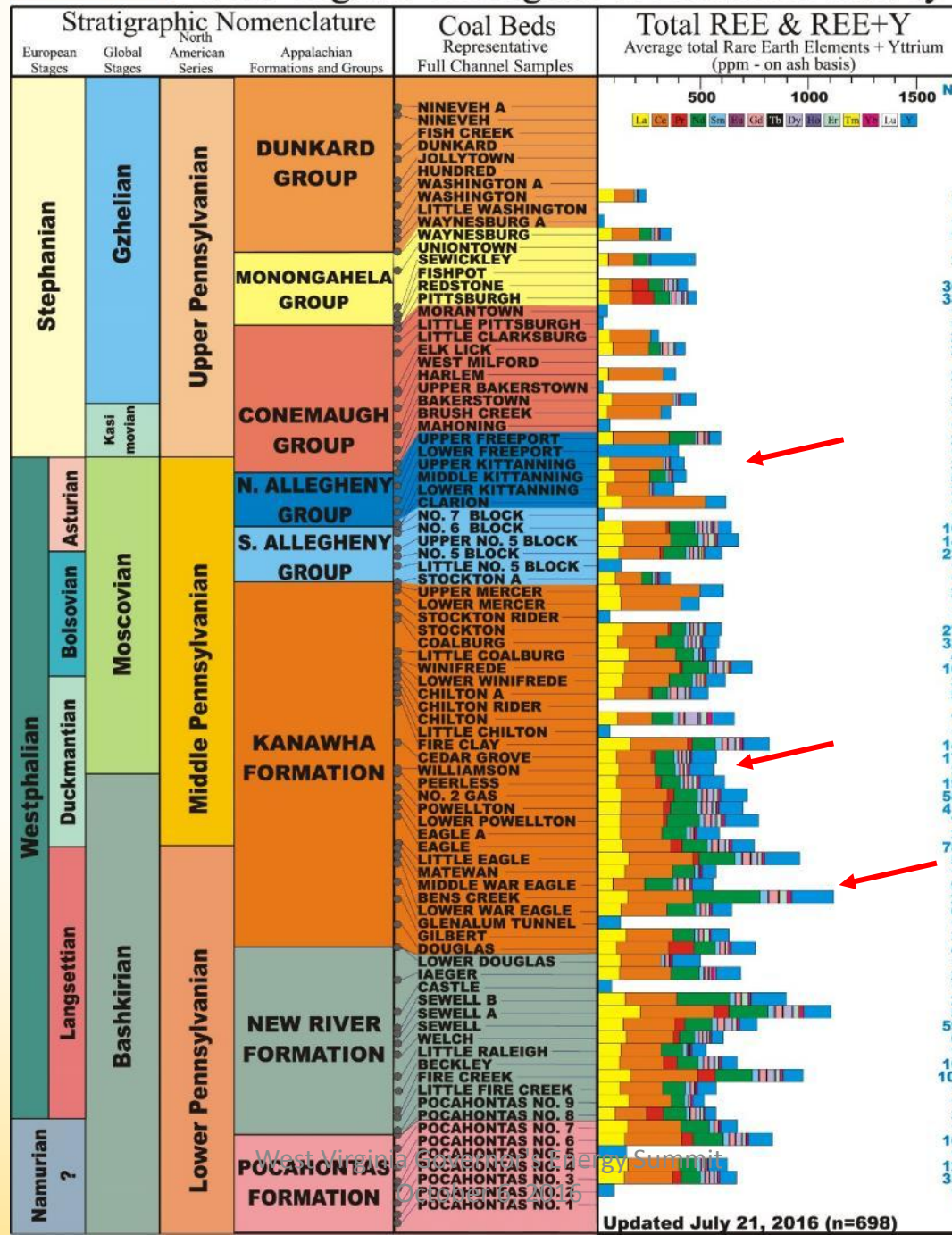


<http://geomaps.wr.usgs.gov/parks/pltec/sc306ma.html>



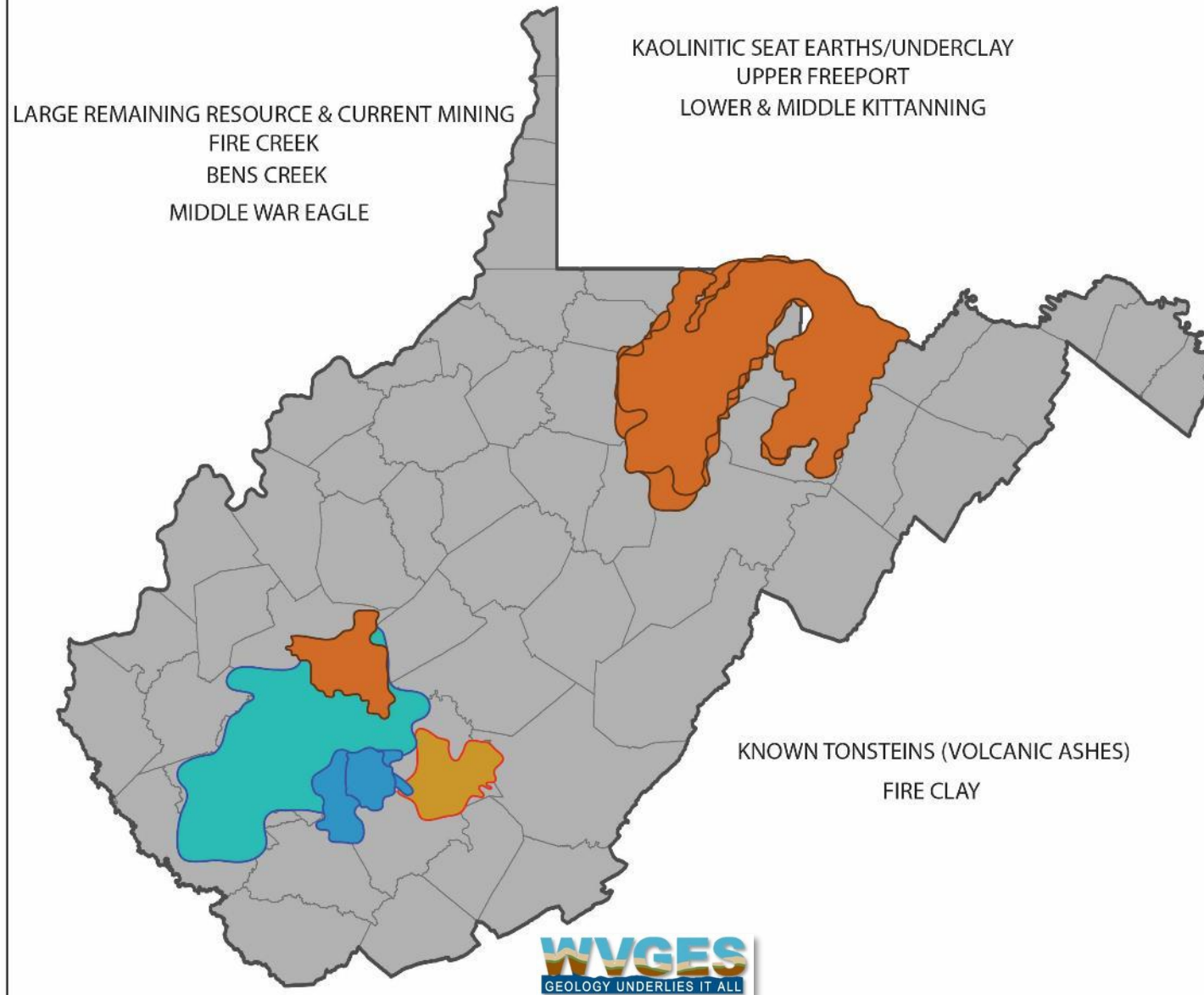
A

<http://www.doccity.com/en/cyclotems-environmental-geology-lecture-slides/380561/>

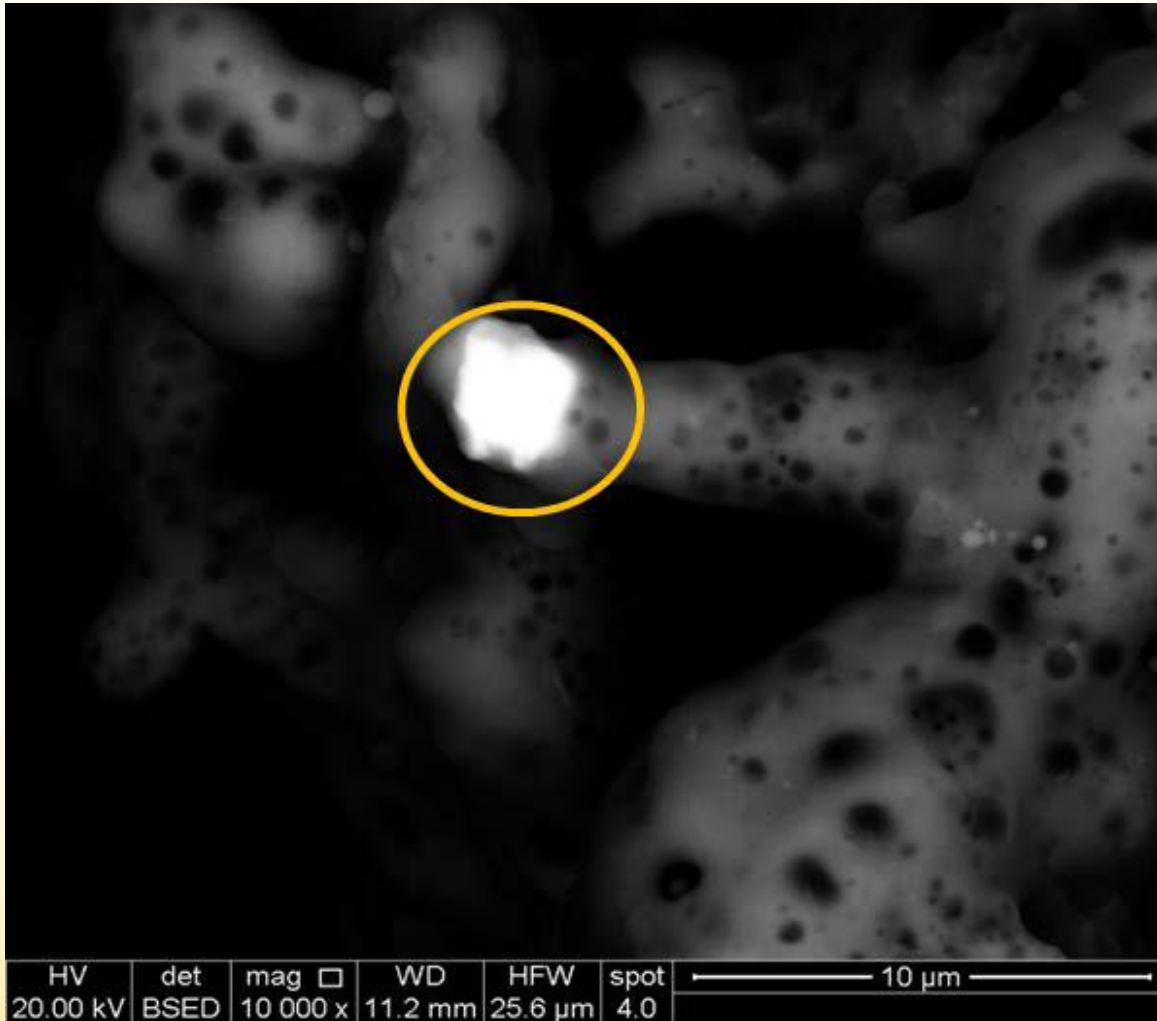


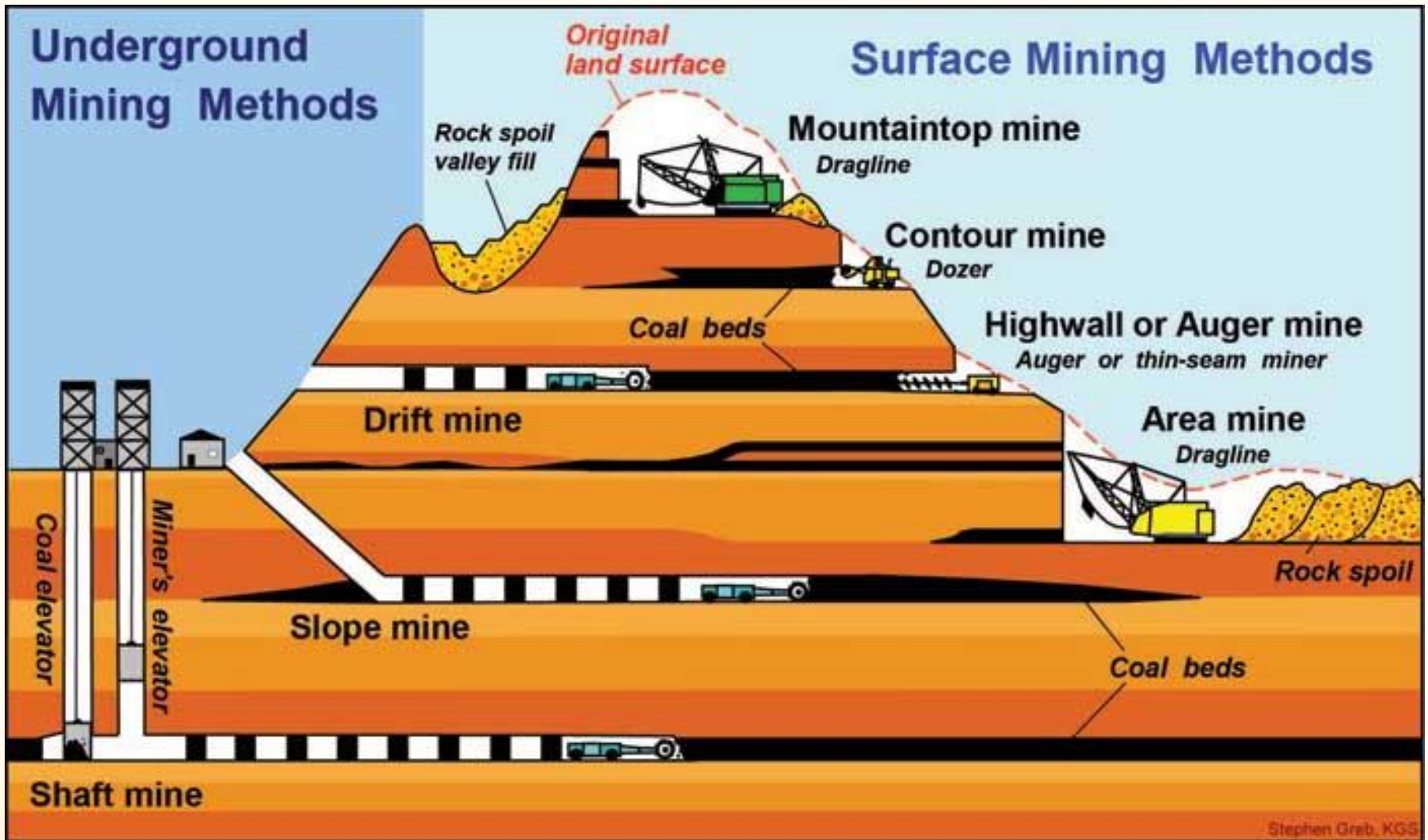
Updated July 21, 2016 (n=698)

WVGES is conducting detailed sampling and research in conjunction with TetraTech in support of NETL award



Challenge 2: Extract REEs from Host Material



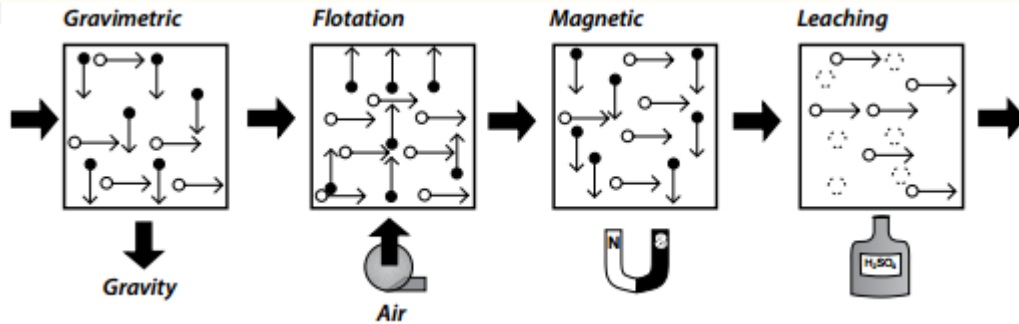


https://www.uky.edu/KGS/coal/images/Coal_mining_methods_med.jpg

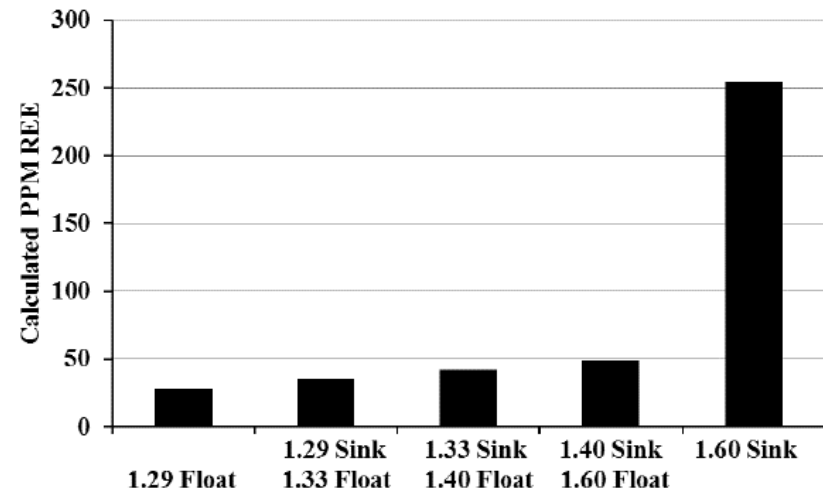
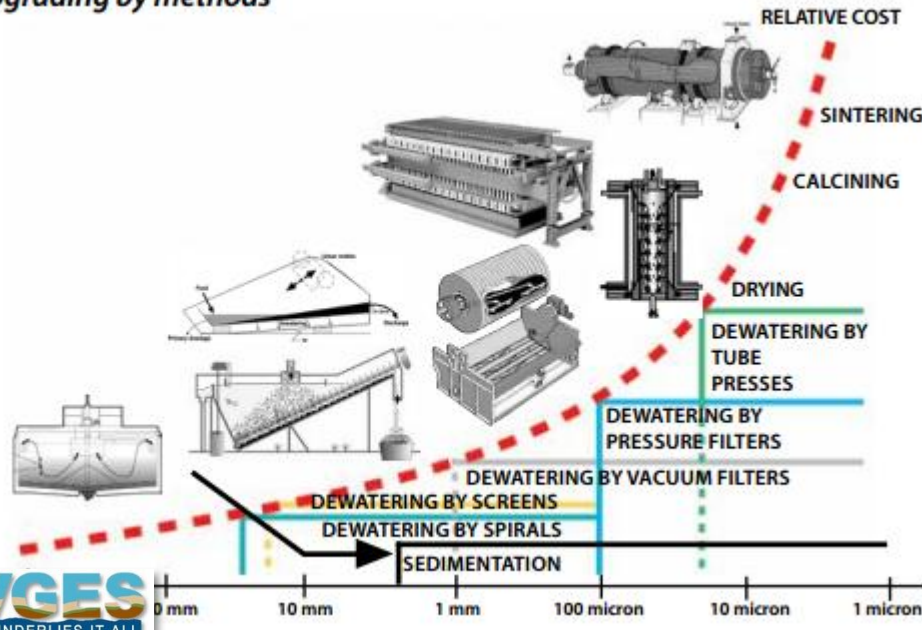
Large volumes of material must be processed to obtain REEs from host rock



Bryan et al., 2015



Upgrading by methods

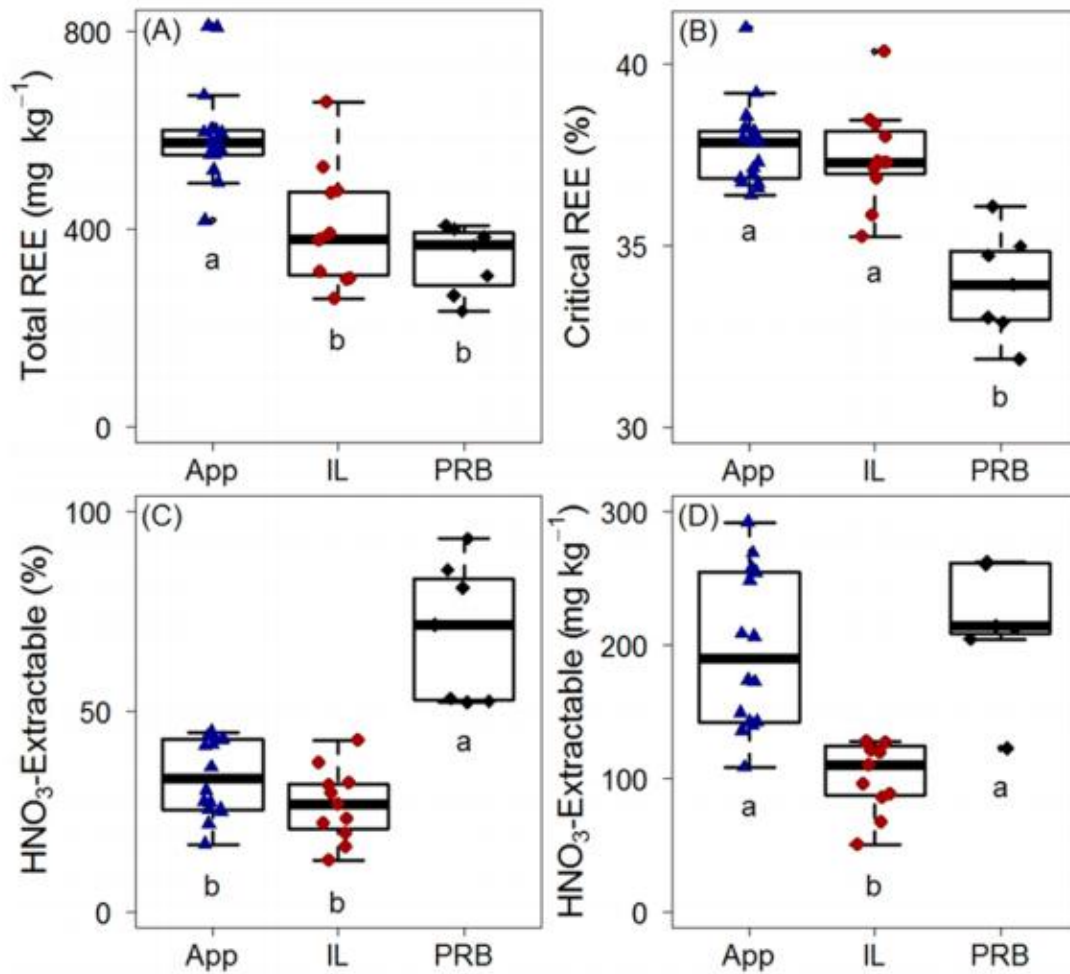


http://www.motioncontrolonline.org/content-detail.cfm/Motion-Control-Technical-Features/Market-Update-Rare-Earth-Magnet-Prices-and-Motion-Control/content_id/322

Post-combustion (fly) ash: Appalachian coals have highest REEs; more difficult to extract due to glassy encapsulation



<http://pubs.acs.org/doi/pdf/10.1021/acs.est.6b00085>



Goal: Water-Soluble Rare-Earth Concentrate



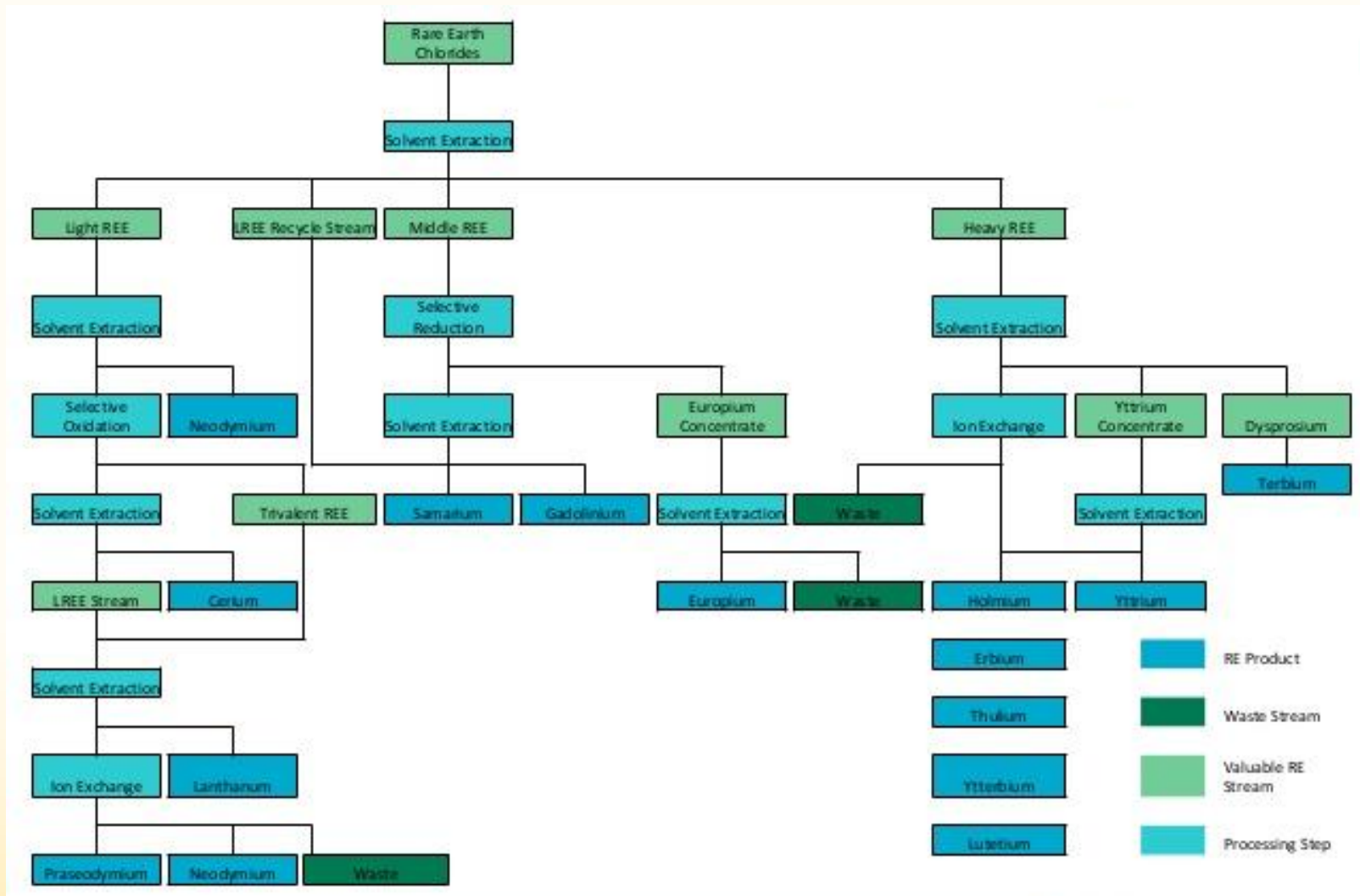
<http://www.wsj.com/articles/lynas-co-digs-in-as-rare-earth-prices-slump-1441097885>

Challenge 3: Separate the Individual Rare Earth Elements



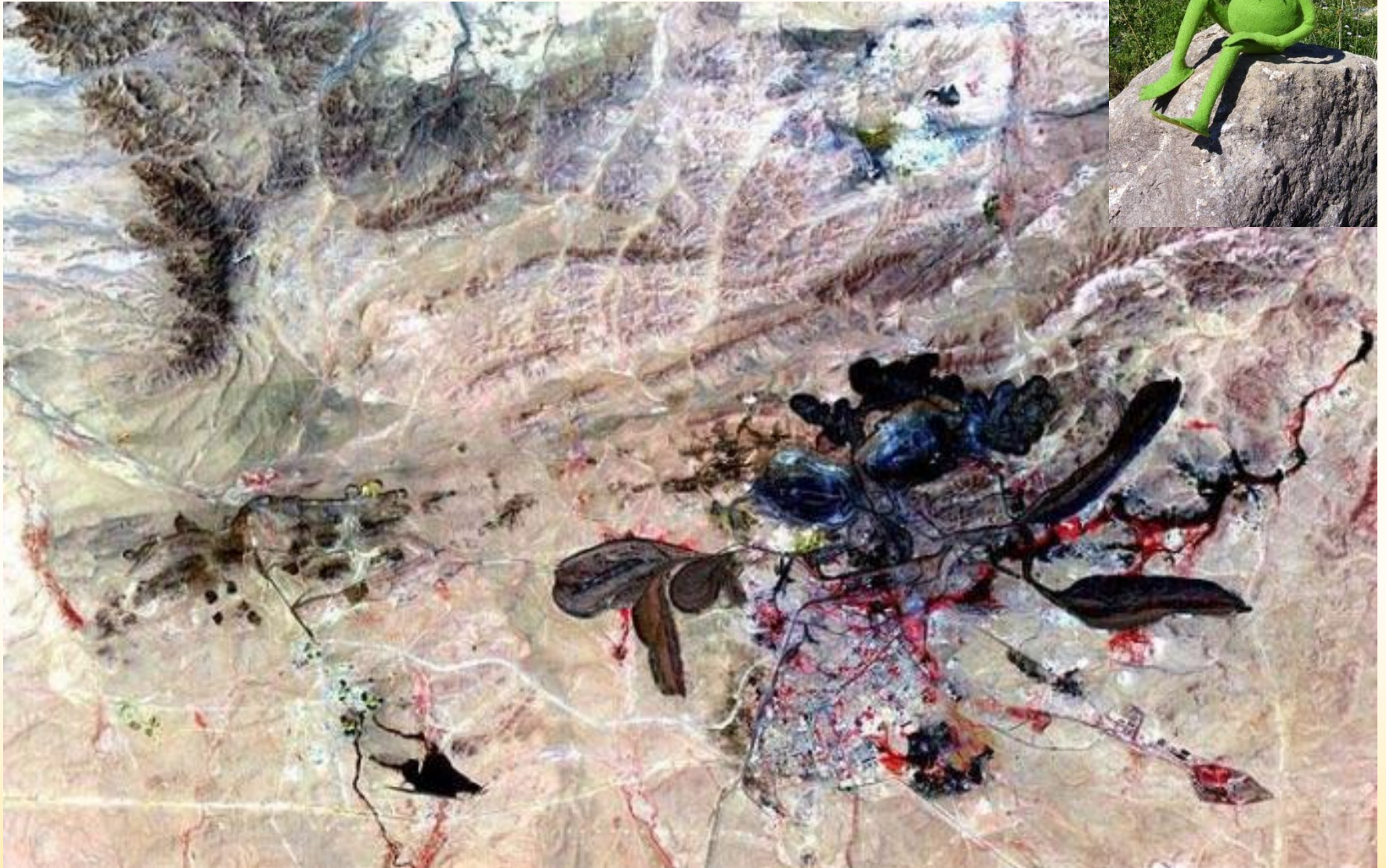
https://en.wikipedia.org/wiki/Rare_earth_element

Traditional Separation Methods: Multiple Steps, Multiple Solvents



<http://www.slideshare.net/CallumBrowning/lca-of-re-production-from-mz>

It's not easy being green...



...but technologies are advancing

White Paper on Separation of Rare Earth Elements, February 20, 2016

Molecular Recognition Technology:

A GREEN CHEMISTRY PROCESS FOR SEPARATION OF INDIVIDUAL RARE EARTH METALS

http://ucore.com/documents/WhitePaper_REE_Separations.pdf

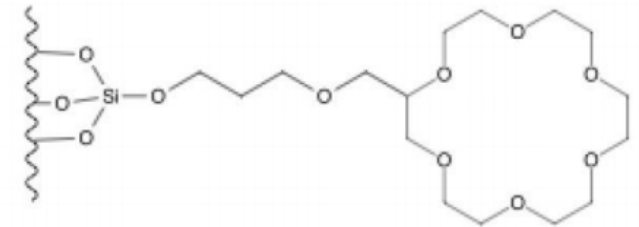
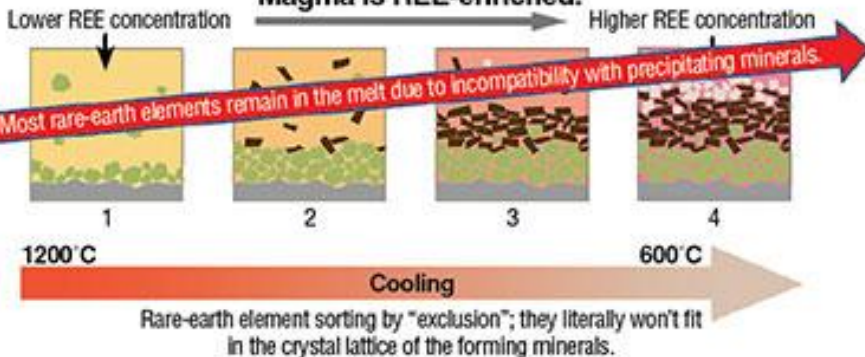


Figure 1

REEs During Fractional Crystallization

Magma is REE-enriched.



LIGANDS



SuperLig®
Ligands attached to solid particles

Solid Particle

- Ligands are customized molecules that attract specific elements
- SuperLig® particles use specialized ligands
- Ligands are covalently attached to SuperLig® particles
- SuperLig® particles fill the column to selectively extract REE



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Advanced Technologies



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MRT Columns

pH Adjustment

Filtration

Precipitation

Control Interface

Treated PLS



MRT Pilot Plant Production

SUMMARY

- Coal measures in WV demonstrate significant resource potential with regard to rare earth elements
- REEs can occur in multiple rock types, and identification of optimal feedstock material is key
- Large volumes of material must be processed at the preparation-plant level; each feedstock stream will require customized processing
- Opportunities exist for recycling of waste products

SUMMARY

- West Virginia possesses the experience, knowledge, and trained workforce to develop and enhance these emerging technologies
- Cooperation and collaboration is essential to overcoming operational challenges





Thank You!

www.wvgs.wvnet.edu