

# Rare Earth Elements in Coal Deposits – a Prospectivity Analysis\*

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## Abstract

We conducted a prospectivity screening of rare earth element concentrations that have been measured in coal deposits across the United States. This work is based on the USGS Coal Quality Database and other selected data obtained from state geologic surveys. A number of papers have been published establishing the link between elevated concentrations of rare earth elements in some coal fields (compared to U.S. average concentrations) and volcanic eruptions that have been dated to the time when these deposits were being laid down. A string of papers since the 1960's has identified this phenomena both outside the United States and in the Western US. More recently, evidence has been found linking at least two potential eruptions that could account for higher levels of rare earth elements in some coals in the Eastern US.

This study sought to identify the information needed to determine whether there might be a potential for commercial extraction of these rare earth elements from coals still being actively produced, from mining wastes or abandoned mines that remains accessible, and from fly ash produced during combustion of these coals. The study is not primarily intended to answer this question but rather to determine what information is available, to organize known information, and to identify key unknowns so that it is possible to assess the economic potential for such an approach.

Based on the data available at this time, we will present several estimates of probable resources originally in place in several key coal formations and estimate of reserves that could be extracted from coal being mined and from residual materials left over from prior coal extraction and use. Amongst the various coal deposits showing elevated levels of rare earths, a number of locations evidence a ratio of heavy REE+Y to light REE of 1-to-1 or 1-to-2. These sources may be of particular interest in terms of spurring regional development.

A means of assessing the potential to gather rare earth containing materials and to extract the rare earth minerals will be offered to define recoverable reserves. The concentrations found in coal deposits, on average, barely approach levels judged commercially viable when extracting the rare earths alongside another mineral. However, the nature of REE –rich mineral matter in coal may provide unique opportunities to separate out the REE-rich minerals from the coal and other minerals while producing two commercial products. Research and development needs and the opportunities that successful development might present will be discussed.

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*China is the top-producing country of rare earth metals. | Reuters*

## **Rare Earth Elements in Coal Deposits – a Prospectivity Analysis**

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James Ekmann, Leonardo Technologies, Inc.

**September 25, 2012**

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# The U.S. May Be “Producing” Over 40,000 Tons of Rare Earth Elements Annually From Coal Mining

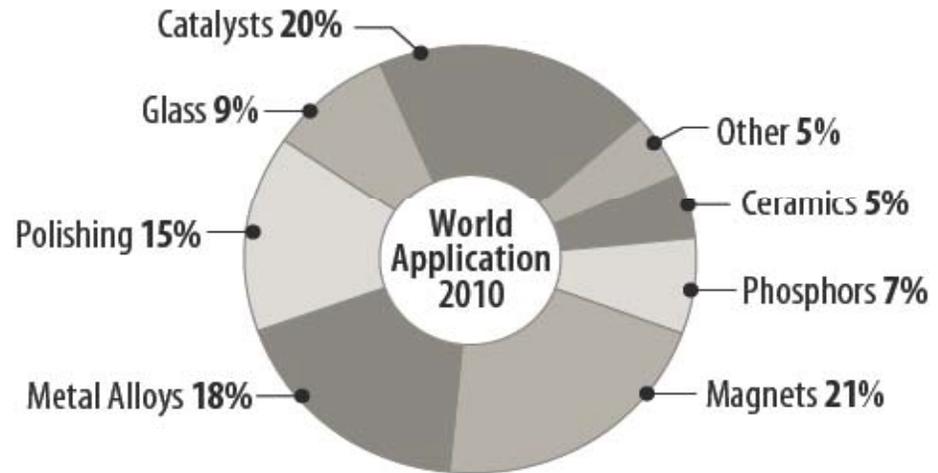
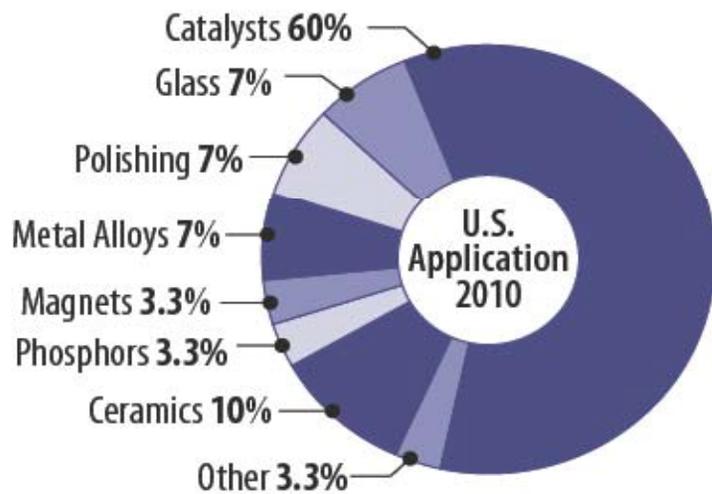
- LTI is conducting a “prospectivity” analysis for the National Energy Technology Laboratory (NETL)
- It is well-known that rare earth elements (REE) can be found associated with commercially important coal deposits
- Substantial data exists in the literature and is held by state geological surveys to suggest that some coal beds and formations contain levels of REE substantially enriched above the crustal average for REE.
- Zones of enrichment can be identified, particularly those under active production and quantities of REE estimated that might be available for extraction annually and the tonnages that remain in proven reserves for these coal deposits.

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*Rare earth elements in coal deposits – a prospectivity analysis, Ekman, J.M.<sup>1</sup>, Richard Noceti<sup>1</sup>, Eric Lopert<sup>1</sup>, Bradley Hartwell<sup>1</sup> Terry Ackman<sup>1</sup> and Timothy Skone<sup>2</sup>*

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2. *National Energy Technology Laboratory*

# Uses for Rare Earth Elements are Growing



Source: IMCOA, 2011 (Note: Figure created by CRS)

Applications	Metals
Hybrid and Electric Vehicles	Nd, Pr, Dy, Tb
Catalytic Converters	Ce, La
Wind Power Generators	Nd, Pr, Dy, Tb
Compact Fluorescent Lamps, LED's	Y, Eu, Tb
Hard Disk Drives	Nd, Pr, Dy, Tb
Flat Panel Display Screens	Y, Eu, Tb, Gd, Pr, Ce
Medical Applications	Nd, Pr, Dy, Tb, Y, Eu
Portable Electronics and Small Motors	Nd, Pr, Dy, Tb, Y, Eu

# REE Global Production and Reserves

Country	2010 Production <sup>1</sup>	2011 Production <sup>1</sup>	Estimated Reserves <sup>1</sup>	HREE + Y Demand
China	130,000	130,000	55,000,000	NA
U.S.	(2)	(2)	13,000,000	NA
Rest of World	~3000 <sup>e</sup>	~3000 <sup>e</sup>	42,000,000	NA
Total	~133,000	~133,000	110,000,000	15,894 <sup>3</sup>

e. Estimated

1. Data in metric tons

2. Mountain Pass mine began production from new mining activity in 2012; REE products were being produced from stockpiles between 2007 and 2011.

3. Total of five heavy rare earth elements in use in 2010 (consumption projected to grow to 18845 by 2015).

U.S. Geological Survey, Mineral Commodity Summaries, January 2012

*Mountain Pass mine resumed production in early 2012. The Wall Street Journal reported that “Molycorp Inc. (MCP) reported that more than three-quarters of the Phase 1 rare-earth production at its flagship California manufacturing facility has been committed, helping the rare-earth mining company meet its allocation target for last year.” <http://online.wsj.com/article/BT-CO-20120103-703756.html> January 3, 2012*

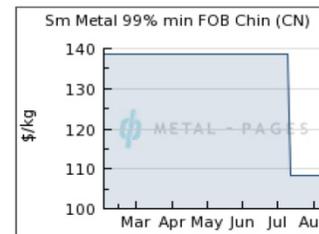
# Current Sources and Price Volatility

- China currently dominates global production and sales
- Costs for developing new resources can be high – price volatility can complicate decision
- Co-production – as occurs in China - can reduce costs and risks

Quoted prices for rare earth metals and oxides on March 5, 2012

Metal	Last Price	% Week	% Year	31/12/2011	Units
Lanthanum metal ≥ 99%	-17 45.00	-27.4%	-27.4%	62.00	US\$/kg
Lanthanum Oxide ≥ 99.5%	-16.0 19.00	-45.7%	-45.7%	35.00	US\$/kg
Cerium metal ≥ 99%	-35.0 45.00	-43.8%	-43.8%	80.00	US\$/kg
Cerium Oxide ≥ 99.5%	-14.0 16.00	-46.7%	-46.7%	30.00	US\$/kg
Praseodymium metal ≥ 99%	-90.0 160.00	-36.0%	-36.0%	250.00	US\$/kg
Praseodymium Oxide ≥ 99.5%	-21.0 99.00	-17.5%	-17.5%	120.00	US\$/kg
Neodymium metal ≥ 99.5%	-110.0 170.00	-39.3%	-39.3%	280.00	US\$/kg
Neodymium Oxide ≥ 99.5%	-10.0 120.00	-7.7%	-7.7%	130.00	US\$/kg
Samarium metal ≥ 99.9%	0.0 150.00	0.0%	0.0%	150.00	US\$/kg
Europium Oxide ≥ 99.5%	-1900.0 1,950.00	-49.4%	-49.4%	3,850.00	US\$/kg
Gadolinium metal 99.9%	-40.0 210.00	-16.0%	-16.0%	250.00	US\$/kg
Gadolinium Oxide ≥ 99.5%	-5.0 135.00	-3.6%	-3.6%	140.00	US\$/kg
Terbium metal ≥ 99.9%	0.0 3,300.00	0.0%	0.0%	3,300.00	US\$/kg
Terbium Oxide ≥ 99.5%	-800.0 2,000.00	-28.6%	-28.6%	2,800.00	US\$/kg
Dysprosium metal ≥ 99%	-1500.0 1,200.00	-55.6%	-55.6%	2,700.00	US\$/kg
Dysprosium Oxide ≥ 99.5%	-700.0 800.00	-46.7%	-46.7%	1,500.00	US\$/kg
Erbium metal ≥ 99.9%	-75.0 275.00	-21.4%	-21.4%	350.00	US\$/kg
Erbium Oxide ≥ 99.5%	+5.0 180.00	2.9%	2.9%	175.00	US\$/kg
Yttrium metal ≥ 99.9%	-10.0 160.00	-5.9%	-5.9%	170.00	US\$/kg
Yttrium Oxide ≥ 99.99%	0.0 95.00	0.0%	0.0%	95.00	US\$/kg
Scandium metal 99.9%	-3000.0 15,000.00	-16.7%	-16.7%	18,000.00	US\$/kg
Scandium Oxide ≥ 99.95%	0.0 7,200.00	0.0%	0.0%	7,200.00	US\$/kg
Mischmetal ≥ 99%	-6.0 23.00	-20.7%	-20.7%	29.00	US\$/kg

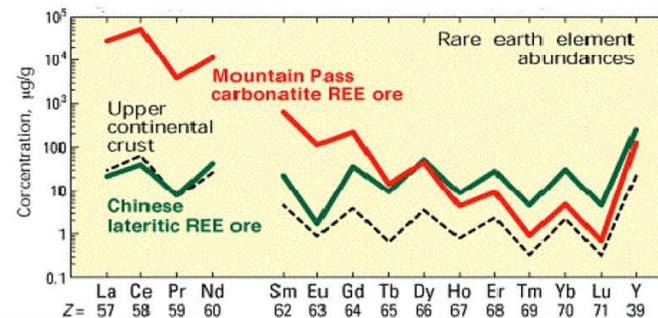
Source: <http://www.mineralprices.com/default.aspx#Rare> quoting HEFA Rare Earth



Presenter's Notes: Price volatility makes economic assessment of any deposit complex. Rare earth only projects may face a different hurdle rate-of-return than co-production projects. Would extracting REE from coal being actively mined or from coal mining wastes that have already been mined and processed be an economically attractive option? This paper examines the concentrations of REE associated with selected coals, the mineral forms, and the fate of the REE minerals during processing and end use to create a structure for such an economic analysis. USGS price trend reports include a variety of REE products including concentrates, mischmetal (a multi-element blend) and various other forms. Refining the ores to yield pure metals or pure metal oxides can be very expensive.

## Crustal Averages for Occurrence of Earth Elements

- A Province of Ontario government report referenced work by Sinton (2005) that provided an estimate on the crustal abundance (~175 ppm) by rare earth element.
- USGS publication SIR10-5220 (USGS, 2010) presents results from a number of studies. The REE concentrations report range from a low of ~160 to a high of ~242 although most of the studies report a total less than 210.
- The primary differences appear to be between the measured concentrations of lanthanum, cerium, and neodymium in each of the individual studies.



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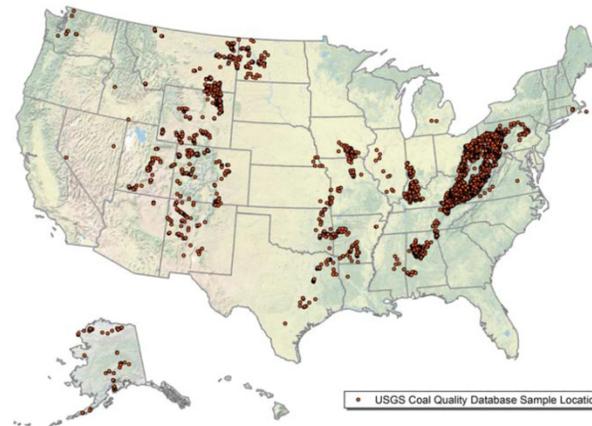
NATIONAL ENERGY TECHNOLOGY LABORATORY

Presenter's Notes: Although the definition of rare earth elements varies by source, we are focusing on the lanthanides (La, Ce, Pr, Nd, SM, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and yttrium (Y). Other sources include scandium and the actinides (including thorium and uranium) amongst rare earths. The first four lanthanides are considered light rare earth elements (LREE) while the remaining elements in the lanthanide series plus yttrium are considered heavy rare earths (HREE). Typical assessments of ore bodies bearing REE reported estimated levels of total rare earth oxides (TREO – elements as oxides) and LREO or HREO. For co-production applications, such as the Chinese lateritic ore, total REE concentrations exceeding 0.3% have been considered as commercially viable.

Sinton, C.W., 2005, Study of the rare earth resources and market for the Mt. Weld Complex: BBC Research, 33 p., unpublished report.

## Occurrence of REE Associated with Coal Formations

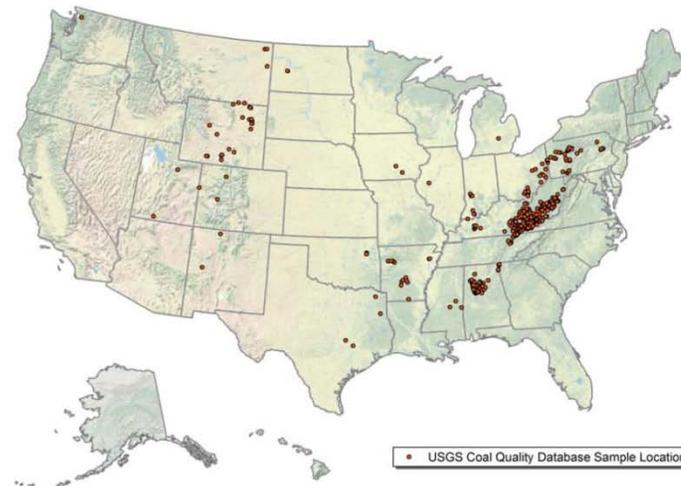
- Papers from the Kentucky Geological Survey and from the West Virginia Geological and Economic Survey present data on REE concentrations associated with coal deposits.
- Some deposits show significantly higher amounts of REE closely associated with the coal than crustal average.
- Other work has identified REE associated with coal in Western U.S., Europe and Asia
- We assessed amount of REE in coal using best source of data for U.S. coals – USGS COALQUAL data base (based on REE content reported on a whole coal basis but measured in the ash.) .



Presenter's Notes: When looking for highest concentrations, we converted data back to REE in ash before sorting the database. We are describing the results as a "mineral matter only" basis although the data is from an analysis of the material left behind when the coal is ashed by standard ASTM methods. The samples in the COALQUAL database (V2) come from the states and from USGS samples. USGS integrated sequential core samples to develop single representations of a whole core for a given location. The data is intended to be representative of the whole core for a given deposit (coal seam, formation, etc.). A number of issues existed within V2 of this database, which USGS is in the process of addressing. We were allowed to review the updated version and the improvements that have been made. We feel that our major conclusions – primarily qualitative assessments of high versus medium versus low levels - remain valid when comparing V2 with V3 results.

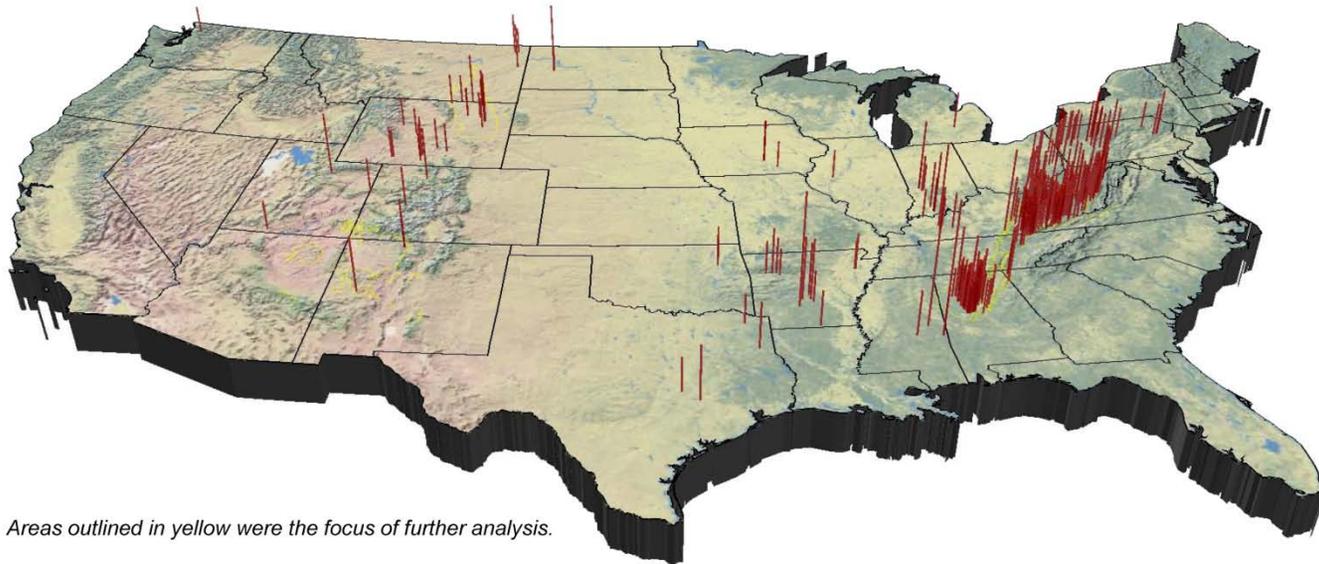
## A Limited Number of Coal Deposits Scattered Around U.S. Exhibit High REE Occurrences

- Figure shows all samples (each representing a core of the complete deposit) where the MMO-only REE value exceeded 1000 ppm.
- Highest concentrations limited to a few seams and formations.
- Further analysis focused on four regions that exhibited a large percentage of all samples with REE > 700 ppm.



Presenter's Notes: The four regions identified as having a significant number of sampled locations that exhibited levels of REE greater than twice the average for all coals are shown in figure (in fact, these samples ranged from twice to more than six times the average for all coals). These four regions are the Central Appalachian Basin (CentAPP), the Southern Appalachian Basin (SoAPP), the San Juan Basin (RckyMtn4Crns), and the Powder River Basin (PRB). Subsequent queries were conducted searching for all samples with REE+Y>850 ppm and REE+Y>700 ppm. Based on this last criterion, 58 samples were identified in the PRB, 21 in the RckyMtn4Crns, 329 in the SoAPP and 675 in the CentAPP respectively for 1,083 out of the full data set of 7430 samples (15%).

## Locations where REE Exceeds 1000 ppm

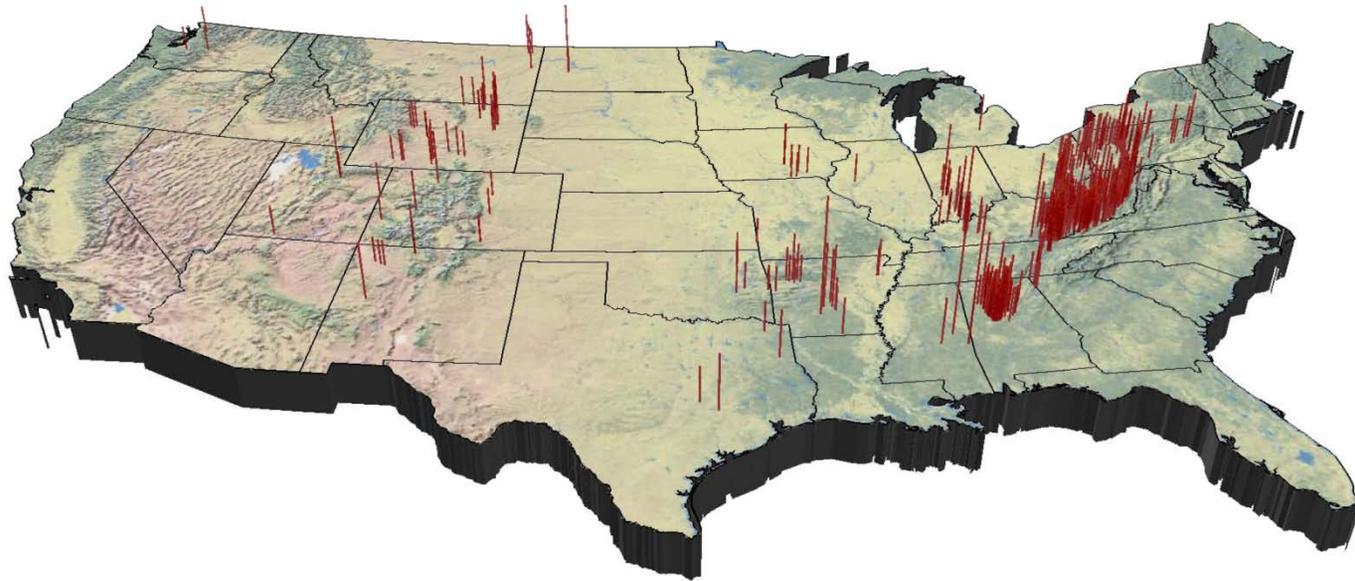


### Presenter's Notes:

#### Sample Location Exceeds 1000 ppm with "Hot Spot" Locations

- USGS Coal Quality Database (COALQUAL version 2.0) sample locations that exceed 1,000 ppm.
- 495 sample location
- Column height is proportional to REE concentration

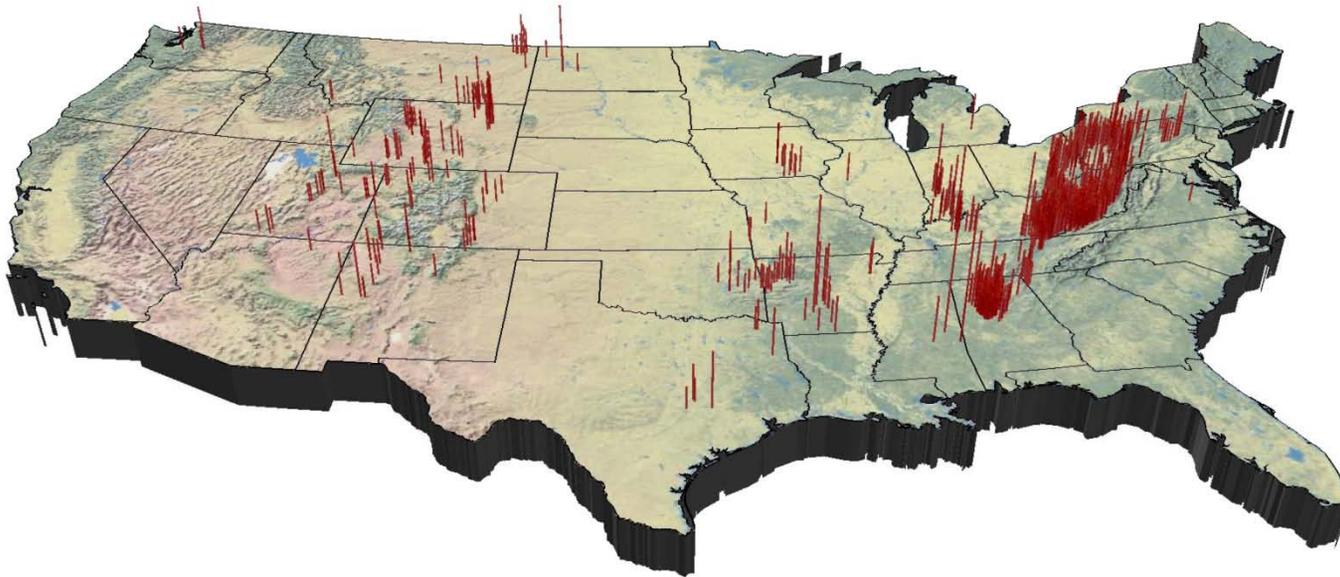
## REE Exceeds 850 ppm



### Presenter's Notes:

- USGS Coal Quality Database (COALQUAL version 2.0) sample locations that exceed 850 ppm.
- 892 sample locations
- Column height is proportional to REE concentration

## REE Exceeds 700 ppm

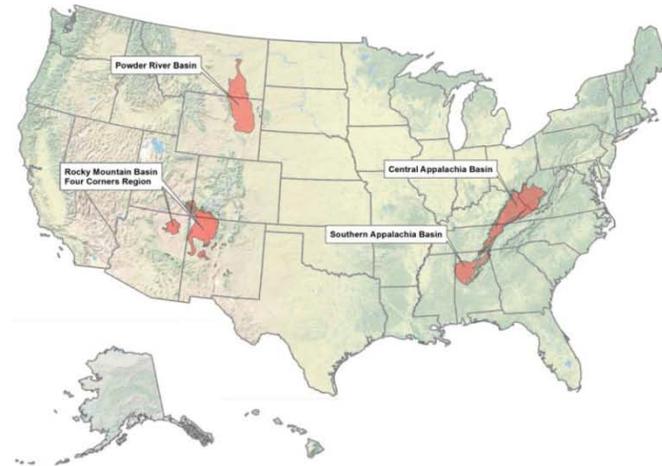


### Presenter's Notes:

- USGS Coal Quality Database (COALQUAL version 2.0) sample locations that exceed 700 ppm.
- 1,725 sample locations
- Column height is proportional to REE concentration

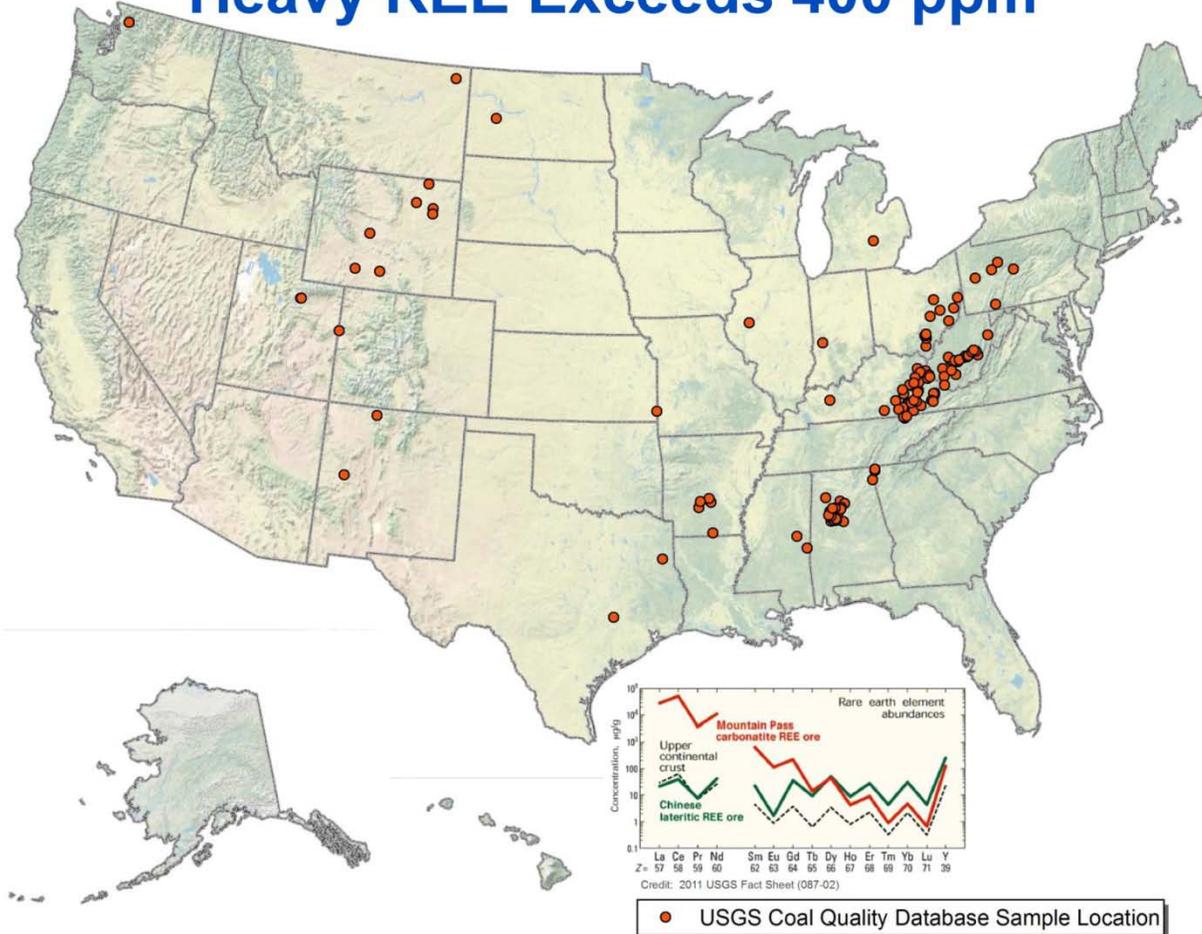
## Data in the USGS Database Also Indicated a Significant Amount of HREE + Y

- Not all rare earth element deposits contain a significant percentage of heavy rare earth elements (which includes yttrium).
- Assessment of candidate regions suggests that HREE+ Y represented 25 to 40% of total REE for the samples in the COALQUAL database.
- Average concentration for all samples with total REE > 700 ppm in each of the four regions examined was between 900 and 1000 ppm.



Presenter's Notes: Not all coals in any of these basins contain elevated levels of REE. However, these four provided significant geographic coverage and were linked to major producing coalbeds. Each of the regions show a substantial increase in the number of samples meeting the search criterion as the concentration limit is lowered. It should also be noted that even with the concentration limit set to include all samples with REE > 700 ppm, the average concentration for these 1,083 samples (15% of all samples in USGS COALQUAL database) approach 1,000 ppm (930 ppm for RckyMtn4Cnrns, 950 ppm for CentAPP, 953 ppm for PRB, and 966 ppm for SoAPP). These values can be viewed as supporting the argument that the higher concentration areas evaluated map a zone of elevated REE. If one looks only at the heavy rare earth elements plus yttrium, the respective values are 229 ppm (RckyMtn4Cnrns), 242 ppm (CentAPP), 206 ppm (PRB) and 240 ppm (SoAPP)

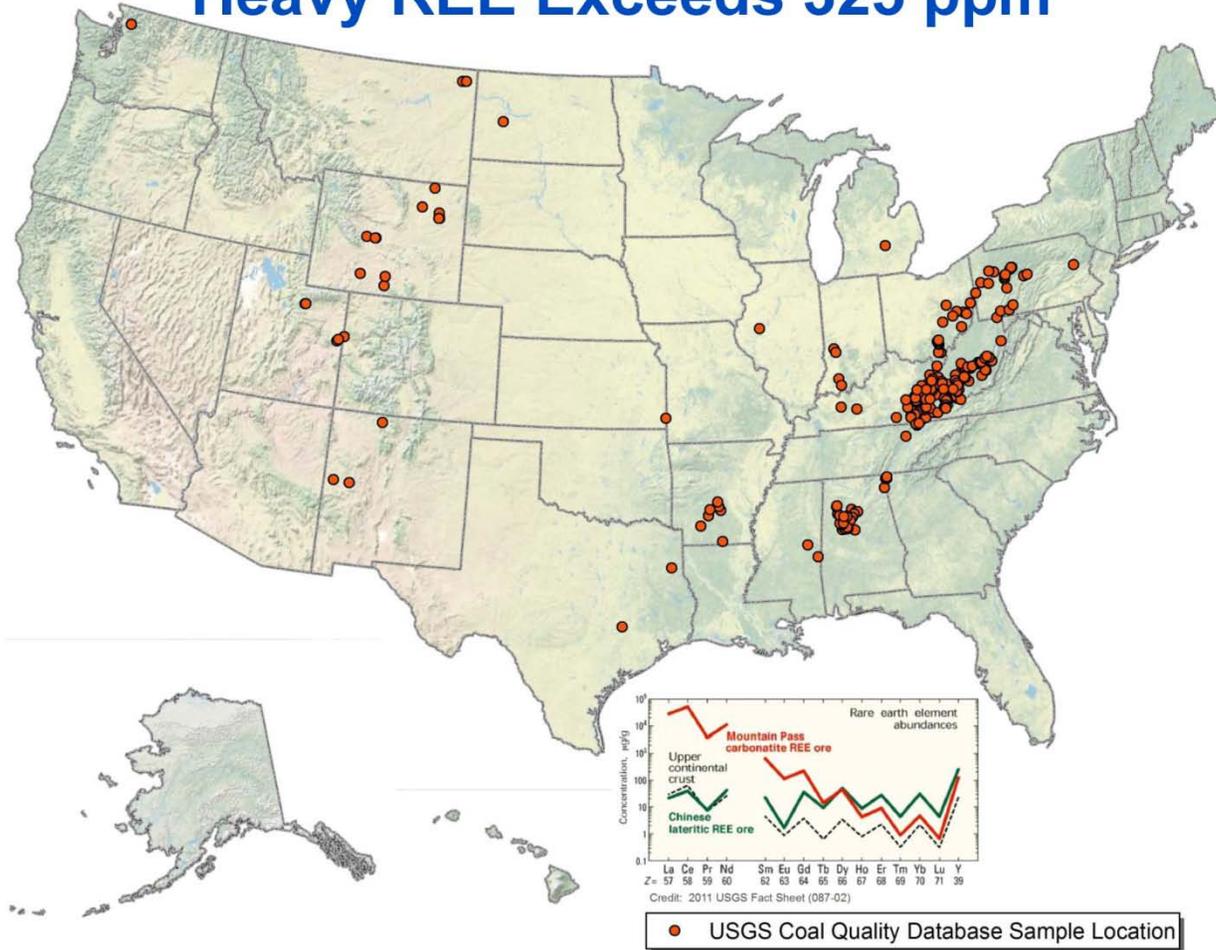
## Heavy REE Exceeds 400 ppm



### Presenter's Notes:

- Total REE, light plus heavy, exceeds 700 ppm and heavy exceeds 400 ppm
- 139 sample locations

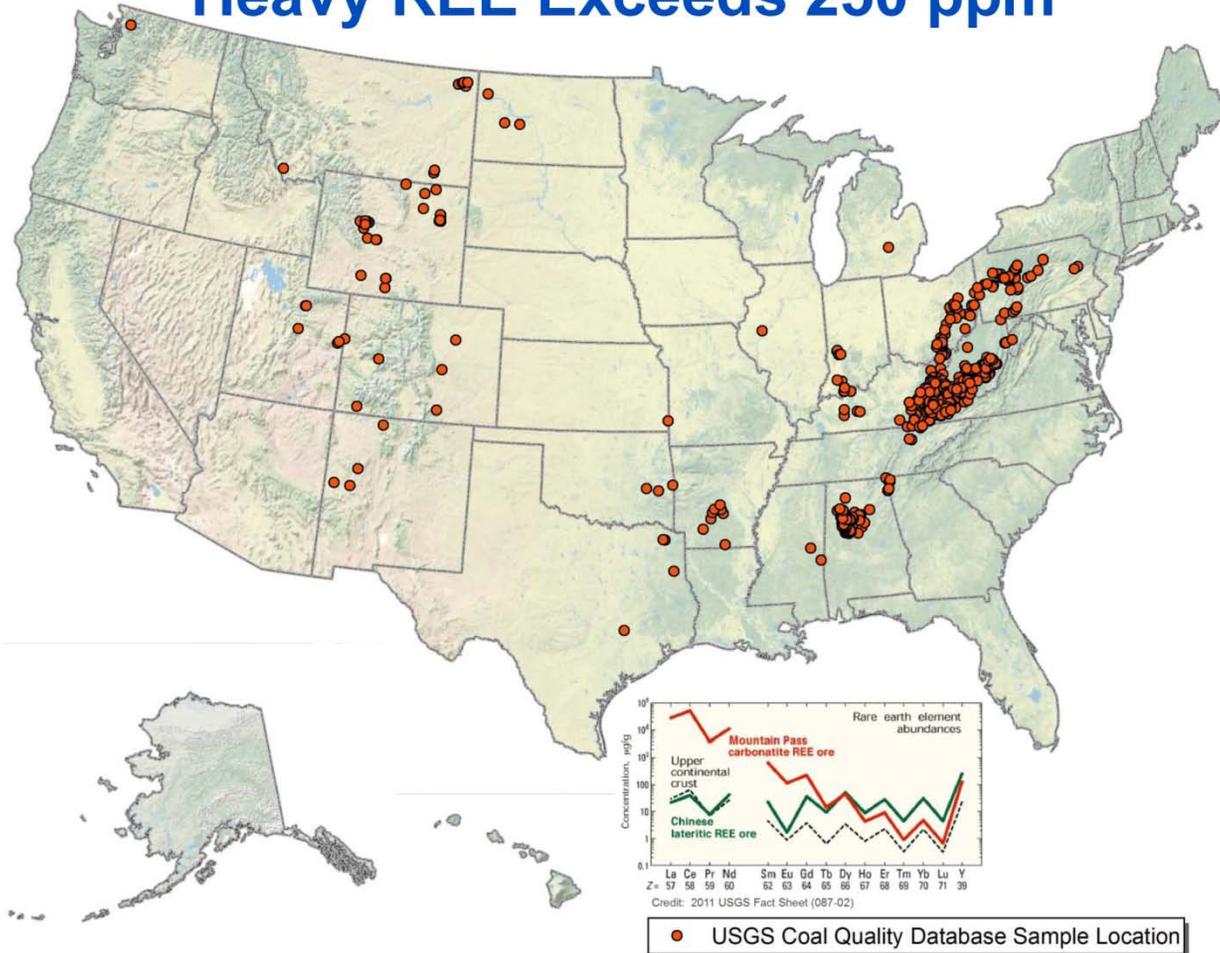
# Heavy REE Exceeds 325 ppm



## Presenter's Notes:

- Total REE, light plus heavy, exceeds 700 ppm and heavy exceeds 325 ppm
- 258 sample locations

## Heavy REE Exceeds 250 ppm

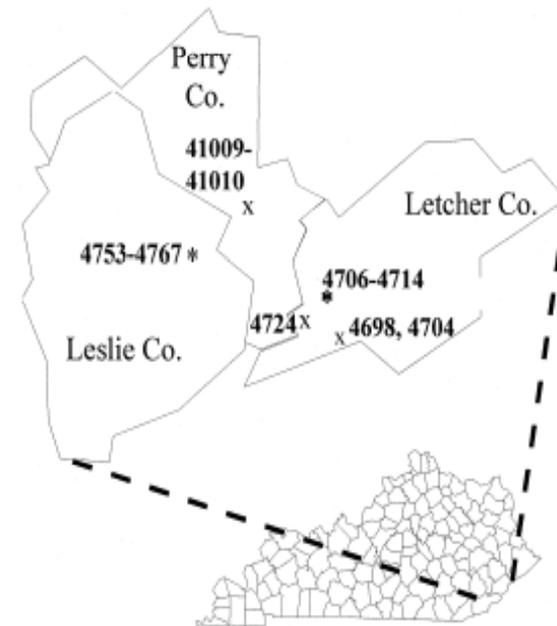


### Presenter's Notes:

- Total REE, light plus heavy, exceeds 700 ppm and heavy exceeds 250 ppm
- 574 sample locations

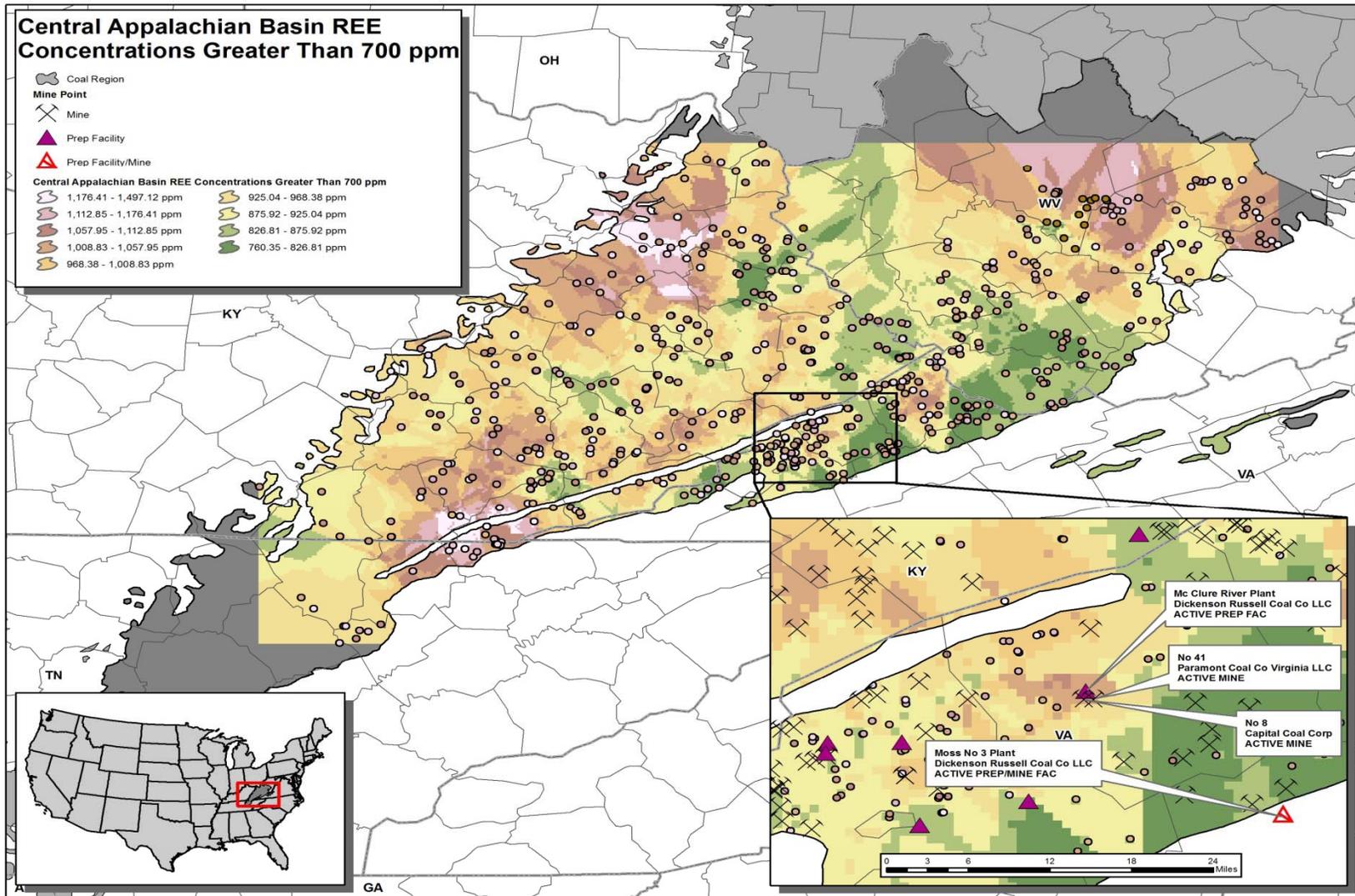
# Are the REE Concentrations Homogeneous Within a Given Coal Deposit?

- Although the database we used included a large number of samples, the coverage may not be statistically representative of the whole coal deposit or of that portion that is commercially recoverable.
- In addition, the data is intended to represent a complete core from the top of the deposit to the bottom. Not all of the deposit might be of interest from a mining perspective.
- The Kentucky Geological Survey published papers in the 1990's that took a few core samples in the Fire Clay coal and analyzed each foot of those samples individually.

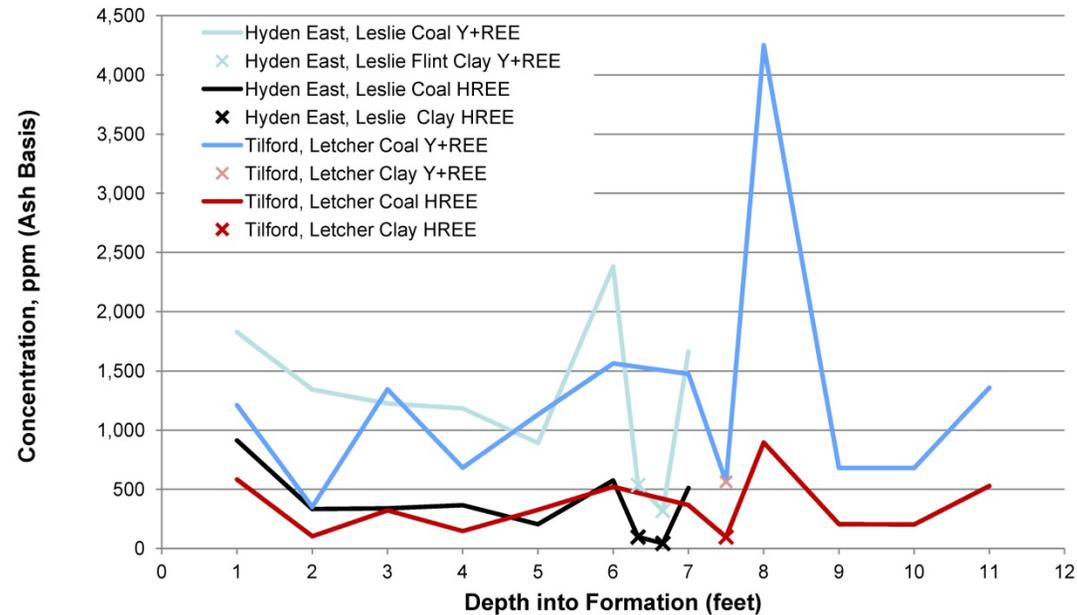


*J.C. Hower, et.al., Lanthanum, yttrium, and zirconium anomalies in the Fire Clay coal bed, Eastern Kentucky, International Journal of Coal Geology 39 (1999) 141 - 153*

# Interpolated REE Concentrations



## REE Not Distributed Uniformly Throughout Coal Bed



J.C. Hower, et. Al., Lanthanum, yttrium, and zirconium *Journal of Coal Geology* 39 (1999) 141 - 153 anomalies in the Fire Clay coal bed, Eastern Kentucky, *International*

Presenter's Notes: Two points can be made:

1. The REE is higher in the coal itself than it is in the clay partings.
2. The lower bench appears (below the partings) appears to have some "zones" of higher concentration value than is found in the upper bench.

For this coal, the lower bench was often left unmined due to its high ash content.

# Why Do We Find REEs Where We Do?

Eastern US - Central App volcanism 300 -325 MYA?

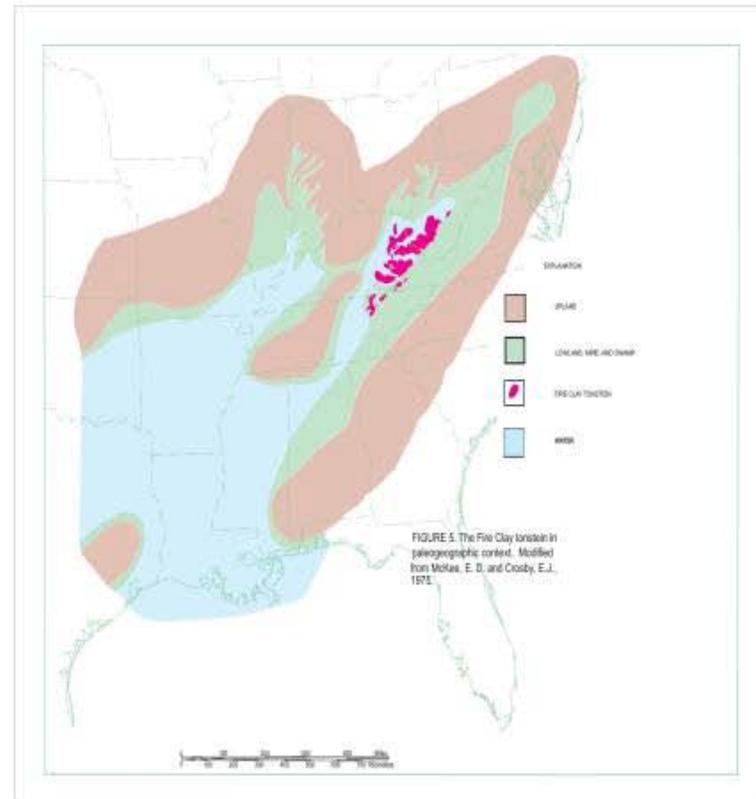
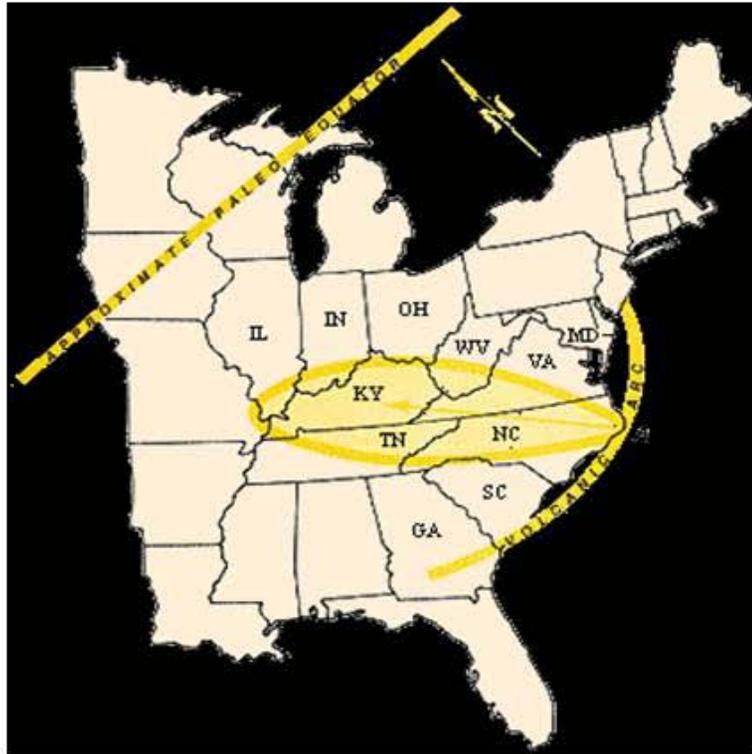


FIGURE 5. The Fire Clay basin in paleogeographic context. Modified from Molnar, E. D. and Crosby, E.J., 1971.

Western US - Laramide Orogeny ~ 35 - 100 MYA or something else?

## Estimated “Unintended Production” and “Resource Potential”

- 10 of top 25 producing seams in 2010 are in regions (EIA<sup>1</sup>) identified with elevated REE concentrations.
- Production estimates use average value for all samples of that coal seam, not just >700 PPM for each coal seam.
- “Unintended production”: Total tonnages of REE+Y associated with coal mined in 2010 exceeds 40,000 tons annually.
- “Unintended production” of heavy rare earth elements and yttrium may exceed 10,000 tons annually.
- Estimated recoverable resources for total REE+Y may exceed 2 million tons for the identified coalbeds and coal formations. Heavy REE+Y may exceed 500,000 tons (based on USGS National Coal Resource Assessment<sup>2</sup>).
- Approach was compromise between estimating percentage of a coalbed exhibiting the higher concentrations of rare earth elements versus using best resource data available. Highlights need for additional data to further assess whether these deposits could have economic value in terms of REE.

1. US DOE Energy Information Agency Report DOE/EIA-0584 (2010), published in 2011

2. Pierce, B.S., and Dennen, K.O., eds., 2009, *The National Coal Resource Assessment Overview: U.S. Geological Survey Professional Paper 1625-F*, 402 p.

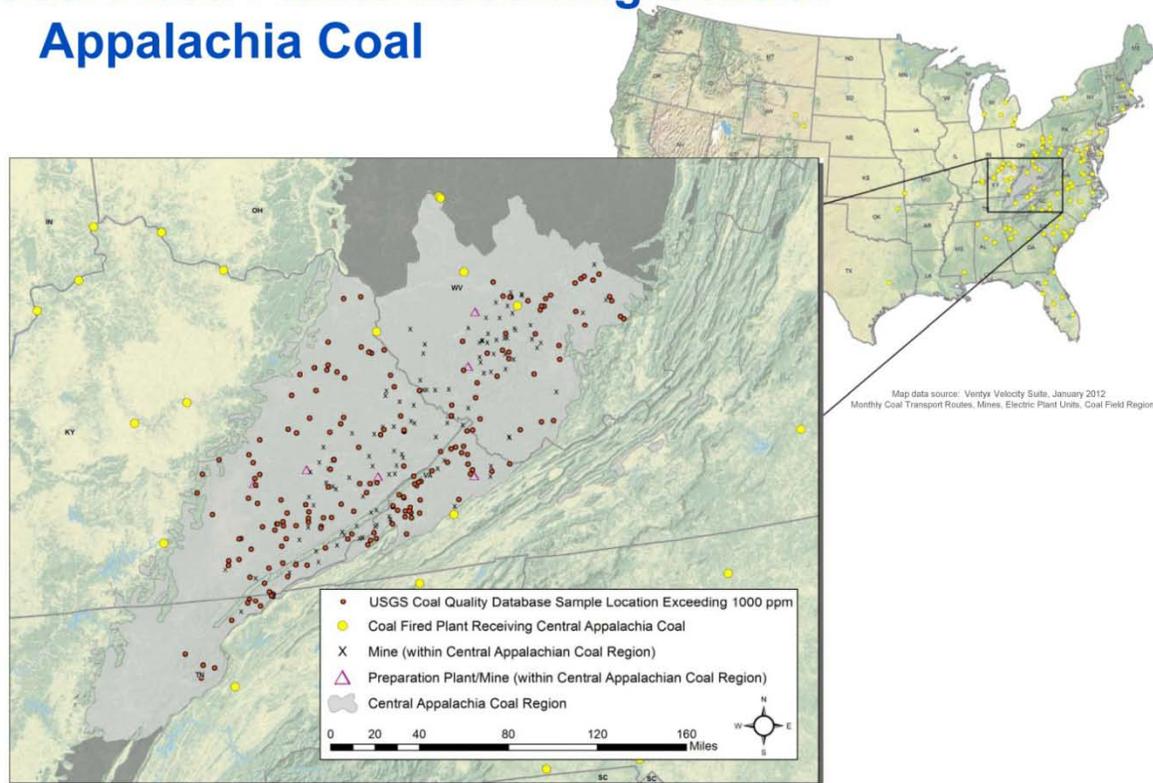
Presenter’s Notes: To assess resources that could be qualified as reserves, the coalbeds listed in the USGS database were mapped onto the EIA list (EIA, 2012) of the top 25 producing coal seams in the United States. Several of these coalbeds (or in some cases coal formations) trend across two or more states and the coalbed name changes with the transition. The top 25 coalbeds were matched (*Presenter’s Notes continued on next page*)

to rare earth concentration data and ten coalbeds or formations were found to exhibit a significant share of the higher measured REE concentrations. Calculations to estimate the amount of rare earth elements that might be actively mined today were developed. Based on data largely available in USGS reports, the estimated recoverable reserves was used to provide an estimate of the total tonnages of rare earth elements that exists in these coalbeds and coal formations. These ten coalbeds or formations currently yield approximately one-half all coal mined in the U.S. The concentration values used in the calculations are not restricted to only the ones that would report as REE+Y>700 but included all coal samples listed in the USGS Coal Quality database for the subject coalbed or coal formation. For instance, the Stockton-Lewiston coal is represented by 22 total samples from 1,708 samples covering the Central Appalachian Basin. Similarly, the Coalburg (Peach Orchard) coal is represented by 72 samples from that same data set, Winifrede by 13, Hazard#4 (Fire Clay/Chilton, Phillips and Windrock) by 38, and Williamson (Amburgy, and Lower Splint) by 22. For the other three basins, total numbers of samples are much less. The Southern Appalachian are represented by 35 samples from the Mary Lee group (Blue Creek coal and Mary Lee coal are both in this group). Wyodak –Anderson is described by 31 samples while the Fruitland #8 is represented by only 10 samples and the Menefee by only 3. The Central Appalachian basin data is far more extensive than any of the other three regions highlighted. The question of representation is an important one that would need to be addressed in going forward with the analysis of the potential to extract REE from mineral matter associated with coal deposits.

# Might an Opportunity Exist to Recover REE From On-going Production?

- Where might one intervene during “unintended production”?
- Is there a chance to extract REEs from coal yet to be mined?
- Could coal now being produced (or still to be mined) be processed by routine coal beneficiation techniques to yield by-product streams of mineral matter with concentrations of rare earths that justify subjecting them to conventional REE extraction processes?
- Could coal derived wastes, either post-use (fly ash for example) or the material rejected during prior mining or coal cleaning could provide pre-concentrated streams of REE that could more readily yield concentrated by-product streams high in REE?.
- There is scant data in the literature that focuses on the presence of rare earth elements in coal preparation tailings, coal fly and bottom ash and in the captured by-products for acid gas removal.

## Coal Fired Plants Receiving Central Appalachia Coal



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NATIONAL ENERGY TECHNOLOGY LABORATORY

### Presenter's Notes:

#### Coal Fired plants receiving Central Appalachia coal

- 201 Sample locations were identified as exceeding 1000 ppm in Central Appalachia Region
- Monthly Coal Transportation Route data was used to associate the Coal Fired Plants with their respective coal source.
- 106 Coal fired plants are associated with coal mines and preparation plants in the Appalachian coal region.
- 120 Coal mines and preparation plants in the Appalachian coal region are associated with coal fired power plants

\*Note: Additional mine and preparation plant locations not identified as being a coal source for plants, via Monthly Coal Transportation Route data, are not shown on this map.

## What is Form of REE-bearing Minerals in Coal, Coal Wastes and Post-combustion Wastes?

- Monazite appears to be the major mineral form for REE associated with coal
  - Other uncommon minerals have been identified in a few studies
- Inorganic association or organic?
  - Bulk of literature suggests that REE is associated with the inorganic phase
  - Yttrium and ytterbium have been found in organic phase
- Affinity with other trace elements?
  - WVGES points out that monazite – the most likely mineral form in which to find rare earths in coal formations – is a detrital material that washed into the coal bed during formation.
  - Tracking REE via affinities or association with other trace elements may be useful predictor of fate during processing.

Presenter's Notes: WVGES points out that monazite – the most likely mineral form in which to find rare earths in coal formations – is a detrital material that washed into the coal bed during formation. Cerium correlates well with the total amount of ash and with non-REE elements, chromium (Cr), scandium (Sc), hafnium (Hf), lithium (Li), tantalum (Ta), vanadium (V) and lead (Pb). The rare earth element, Dysprosium, also correlated well to the presence of other rare earth elements, to the total ash, and to ash related elements such as lithium (Li), thorium (Th), vanadium (V), zirconium (Zr), chromium (Cr) and lead (Pb). WVGES <http://www.wvgs.wvnet.edu/>

## What does the literature say about fate of REEs during coal processing?

- EPA reported that tailing piles have REE concentrations 2-3 times that of feed coal, making tailing piles a potential source for REEs. Cerium, lanthanum, and yttrium were the most prominent REEs, and their concentrations in the prep plant waste stream increased 300%, 307%, and 200%, respectively<sup>1</sup>.
- A recent study from China reports that the REE concentration in tailings piles is more than twice that found in the cleaned coal<sup>2</sup>
- A 2005 USGS report<sup>3</sup> presented results from samples taken at a power plant that was utilizing low-sulfur, low ash sub-bituminous coal from the Wyodak-Anderson (Powder River Basin, Wyoming).
  - Only REE found - monazite crystals trapped in glassy phase
- EPA studies compared concentration of various trace elements in the bottom ash and in FGD residues (sludge). Typically, the rare earth elements were found to be enriched in the bottom ash compared to the FGD sludge; only Erbium, Ytterbium, and Gadolinium were found with ratios of FGD sludge to bottom ash exceeding 1.

1. Trace Element Characterization of Coal Wastes - First Annual Report, Interagency Energy/Environment R&D Program Report, EPA-600/7-78-028, March 1978.

2. Wang, W., Y. Quin, C. Wei, et al. "Partitioning of Elements and Macerals During Preparation of Antaibao Coal," International Journal of Coal Geology, 68, 2006, p223-232

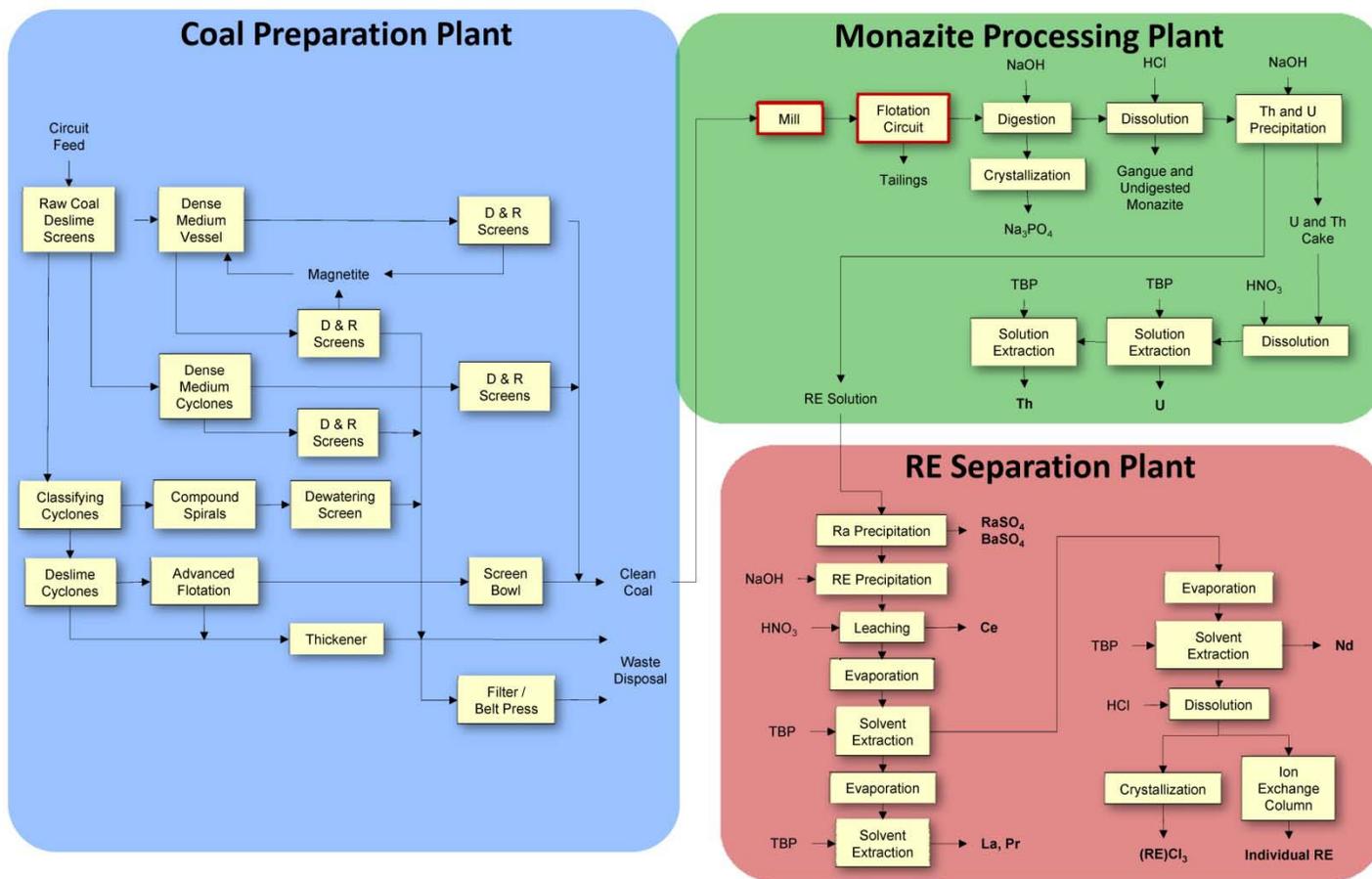
3. Characterization and Modes of Occurrence of Elements in Feed Coal and Coal Combustion Products from a Power Plant Utilizing Low-Sulfur Coal from the Powder River Basin, Wyoming (USGS Scientific Investigations Report 2004-5271, 2005),

Presenter's Notes: A recent study from China looked at how different trace elements (including numerous REEs) partition in various size fractions of Antaibao coal from China. It is clear that the REEs, phosphorous, and thorium all have their high concentrations in the particle sizes 0.5 to 3 mm, and 6 to 25 mm. This suggests that REEs are being present as a phosphate such as monazite. (*Presenter's Notes continued on next page*)

It should also be noted that the REE tailings concentrations are more than twice that of the cleaned coal, further confirming that coal preparation plants can concentrate REEs in tailing piles. Tailing piles receiving high-REE coal may be a valuable place to begin a sample collection campaign (Wang, et al., 2006)

2005 USGS report described a U.S. Geological Survey and the University of Kentucky Center for Applied Energy Research collaboration which focused on a power station operated by an Indiana utility company. This collaborative effort sought to examine the physical and chemical properties of feed coal and coal combustion products from a coal-fired power plant. EPA studies compared concentration of various trace elements in the bottom ash and in FGD residues (sludge). Three separate enrichment ratios, one comparing the concentration in the bottom ash to that in the original coal, a second comparing the concentration in the FGD sludge to the original coal, and a third that reported the ratio of concentrations between the FGD sludge and the bottom ash for 52 trace elements (including all the naturally occurring rare earths and yttrium). Typically, the rare earth elements were found to be enriched in the bottom ash compared to the FGD sludge; only Erbium, Ytterbium, and Gadolinium were found with ratios of FGD sludge to Bottom ash exceeding 1 (1.0, 1.4 and 1.6 respectively).

# Relevant Processing Technology



Presenter's Notes: We have not explored processing schemes other than to develop notional flow charts that mate to current REE processing schemes. A significant cost in REE processing is the complex separation of one (or two or three) REE from other REEs and other mineral constituents. Could there be easier pathways when starting with coal? (Presenter's Notes continued on next page)

Monazite processing presents issues compared to extracting REE from bastnaesite: There are two major REE ore minerals from which the REE can be extracted with relative ease: bastnaesite and monazite. Bastnaesite is a fluorocarbonate mineral that contains predominantly either cerium, lanthanum or yttrium. In the world-class rare earth deposit Mountain Pass the bastnaesite ore is processed according to the following scheme: The run of mine material is passing through a cascade of *physical processing* steps: crushing, screening, grinding, flotation and to produce a bastnaesite pre-concentrates from which products with different REO contents are derived in the following *thermal* and *chemical processing* steps. In the following, the RE-chloride solution obtained from digesting the bastnaesite concentrate in hydrochloric acid is passed through a solvent extraction with several mixer-settler steps. The products of this element-selective extraction processes are the separated REE-oxides.

In a typical monazite, processing flow sheet the heavy mineral sand is first mined by dredging or scraping, screened and then concentrated in spiral concentrators. It is then washed, dried, and fed into magnetic separators to remove ilmenite and other magnetic minerals. In a subsequent step, electrically conducting and nonconducting heavy minerals are separated in electrostatic plate separators followed by induced roll separators that help to distinguish induced magnetic from non-magnetic minerals (i.e. xenotime and monazite from zircon). The former two minerals can then be separated by wet table or air table taking advantage of their slightly different specific gravities. The monazite concentrate can then be digested in hot sulfuric acid and partially neutralized. Upon addition of  $\text{Na}_2\text{SO}_4$ , the lighter REE can be precipitated from the sulfuric solution, which holds the remaining heavier REE. (See: <http://www.anzaplan.com/strategic-minerals/rare-earth-minerals/rare-earth-minerals-processing/>)

D & R Screens – Drain and rinse screens; TBP – tributyl phosphate

# Summary

- What do we know?
- What don't we know?
- Is there a way to quickly improve our understanding of REE distribution in known areas of high concentrations?
- Can we suggest other coal beds or formations worth assessing for REEs?
- What constitutes critical data to assess whether REEs can be economically concentrated from existing mining and processing activities in the coal sector?
- How do these sources compare to other energy-related sources (e.g. shale formations)?

# Comparing Estimates of REE in Coal to Current Production in China and US

Source of REE	2010 (Reported) <sup>3</sup>	2011 (Reported) <sup>3</sup>	2012 (Projected) <sup>4</sup>	Estimated Reserves <sup>3,4</sup>
Chinese sources	130,000 mt	130,000 mt	130,000 – 140,000 mt	55,000,000 mt
Mountain Pass mine <sup>1</sup>	4420 <sup>1</sup> mt	8100 <sup>1</sup> mt	~19,000 mt	13,000,000 mt
US coal seams (2010 production) <sup>2</sup>	~40,000 mt (est.)	~40,000 mt (est.)	~40,000 mt (est.)	2,000,000 mt

1. [USGS\\_minerals\\_mcs-2012-raree.pdf](#) (USGS summary data on REE refined from concentrate or stored. Attributed to Mountain Pass site.)

2. Calculated in this study from EIA data on 2010 production by coal seam and USGS compositional data found in COALQUAL v.2

3. [USGS\\_minerals\\_mcs-2012-raree.pdf](#)

4. U.S. coal reserves data from USGS National Coal Resource Assessment ; compositional data from COALQUAL v.2

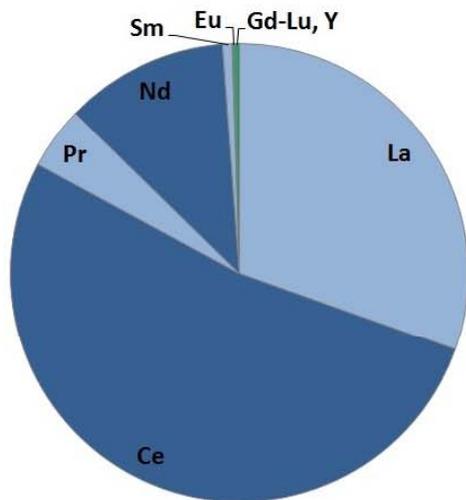
1. At 2010 levels of production, approximately 40,000 tons of rare earth elements may be extracted along with the coal from the ten seams/formations assessed in this study.
2. Nature of the REE inclusions (typically in phosphates) suggests that they would concentrate in coal preparation tailings, in fly ash and in bottom ash.
3. Whether the REE-bearing minerals can be extracted economically from these sources is an open question.

# Comparison of average compositions of various sources of REE

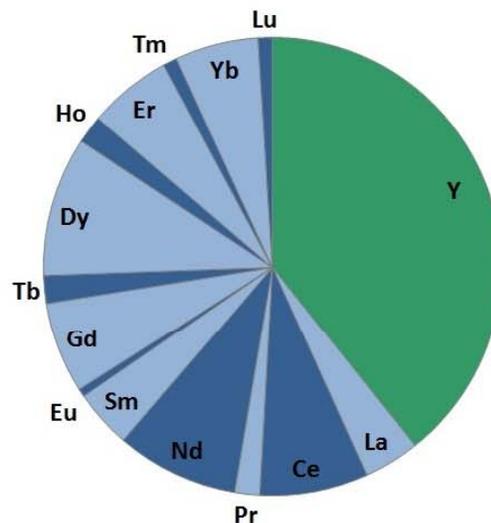
Approximate concentration profiles of rare earth elements at Mountain Pass and in Chinese laterite deposits

Typical concentration profile of REE in Central Appalachian coal

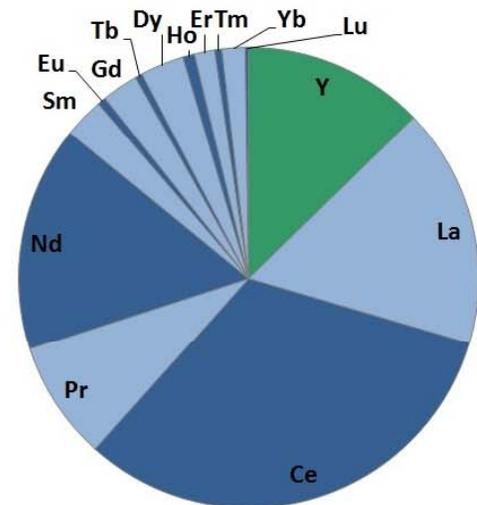
Bastnäsite ore, Mountain Pass, California



Lateritic ore, southern China

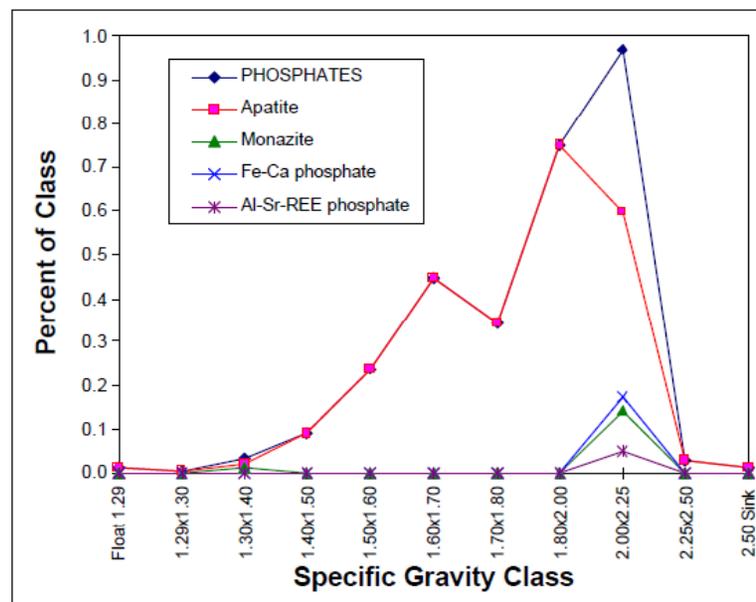
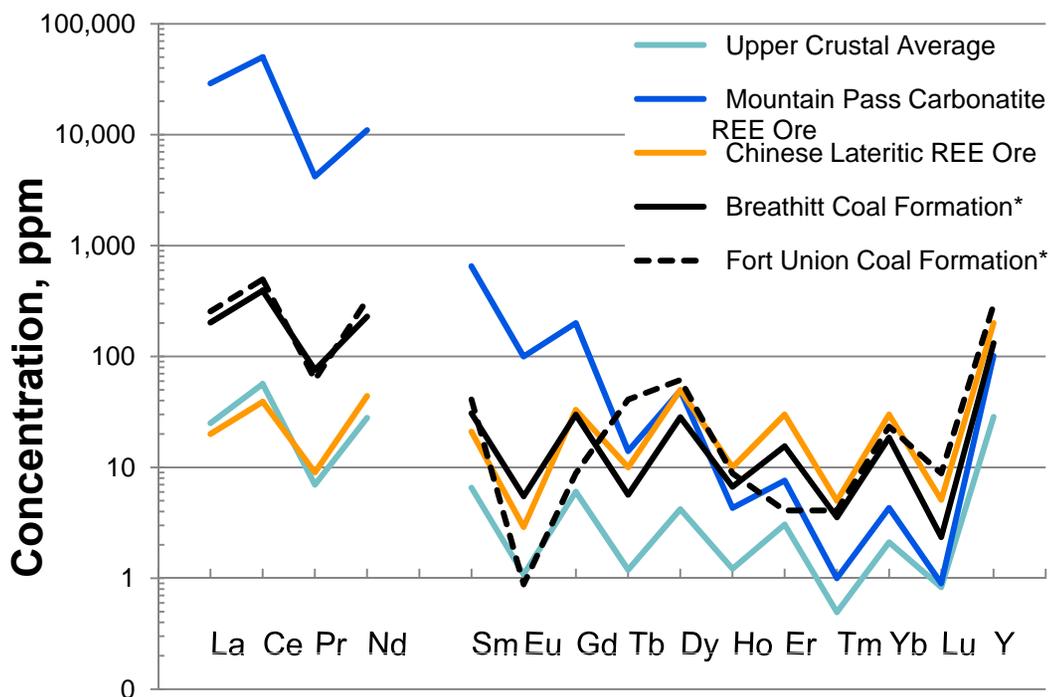


Central Appalachian Coal



# Rare Earth Elements in Coal Mineral Matter are Similar to Concentrations in Chinese Laterite Ore

**Comparison of two commercial sources of REE to crustal average and to REE associated with major coal formations**



**Limited data suggests that REE-bearing phosphates occur in only one specific gravity class.<sup>1</sup> Conventional heavy media separation might concentrate REE-bearing minerals**

# Is There a Role That Other Interested Parties Could Play?

- **Additional sources of data**
  - Current data was not developed to look at REE.
  - Is there available data in state agencies or with others that includes REEs?
- **Access to samples**
  - Assess REE from producing mines.
  - Can we get samples to assess REE in “waste” repositories?
  - Are core samples available for further analysis?
- **Other thoughts**
  - We hope to start a dialog on this subject.

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# BACK-UP SLIDES

# REE Not Distributed Uniformly Throughout Coal Bed

Location	Sample type	Sample	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Hf	Ta	Y+REE	W
Hyden East, Leslie	1 of 11 top	4754	390	140	270	33	130	36	8	40	9	58	12	36	5	33	9	2	1211	30
	2 of 11	4755	67	60	110	12	50	10	2	10	2	10	2	6	0.8	5	2	1	350	10
	3 of 11	4756	190	250	470	54	190	42	5	40	6	37	7	20	3	18	10	3	1345	40
	4 of 11	4757	79	140	240	28	90	20	3	20	3	18	4	11	2	10	10	4	682	8
	5 of 11	4758	210	180	370	44	160	36	4	30	6	35	6	19	3	17	10	2	1132	10
	6 of 11	4759	340	240	470	57	210	49	5	50	8	51	10	30	4	27	10	2	1563	20
	7 of 11	4760	200	270	500	58	200	44	4	40	7	46	9	30	5	29	30	3	1475	20
	flint clay	4761	49	110	200	24	90	19	1	20	2	13	2	6	0.8	4	20	3	564	2
	8 of 11	4762	430	790	1500	190	660	150	13	130	22	130	25	75	11	72	50	3	4251	10
	9 of 11	4763	110	110	210	25	90	22	4	20	4	28	6	18	3	17	10	3	680	7
	10 of 11	4763	120	110	200	26	100	26	6	20	4	24	5	15	2	13	7	2	680	10
11 of 11 base	4767	320	160	360	47	190	51	12	50	10	61	12	36	5	34	8	2	1358	30	
Tilford, Letcher	1 of 7 top	4706	630	220	390	47	190	46	10	60	10	78	17	55	8	54	10	2	1827	20
	2 of 7	4707	210	240	460	53	200	40	5	40	5	33	6	19	3	17	10	2	1343	20
	3 of 7	4708	210	200	400	49	180	40	5	40	6	36	7	20	3	17	10	2	1225	20
	4 of 7	4709	230	190	360	44	170	38	4	40	6	38	7	22	3	19	10	3	1184	10
	5 of 7	4710	120	170	310	36	130	26	3	20	4	25	7	14	2	13	10	3	891	4
	6 of 7	4711	330	430	820	96	350	71	6	70	10	67	13	40	6	38	30	3	2380	20
	flint clay	4712	47	90	190	24	90	19	1	20	2	14	2	6	0.8	5	20	4	535	3
	illitic clay	4713	15	70	120	14	50	11	2	9	1	8	2	4	0.7	4	5	2	318	2
7 of 7 base	4714	320	240	500	60	240	53	9	50	9	64	13	43	7	43	10	2	1663	20	
Tilford, Letcher	flint clay	4698	51	100	190	24	90	1	20	2	13	13	2	6	0.7	4	20	3	546	2
	underlying coal	4704	160	360	740	89	340	72	7	60	9	57	10	30	4	27	50	3	2018	2
Tilford, Letcher	flint clay	4724	55	100	210	25	100	20	1	20	3	15	2	7	1	6	20	3	588	2
Hazard South, Perry	flint clay	41 009	49	100	200	25	90	20	1	20	2	13	2	5	0.7	4	20	3	555	2
	underlying coal	41 010	280	390	770	94	350	73	6	70	10	66	13	40	6	37	30	3	2238	7

All elemental values are on an ash basis.

*J.C. Hower, et al., Lanthanum, yttrium, and zirconium anomalies in the Fire Clay coal bed, Eastern Kentucky, International Journal of Coal Geology 39 (1999) 141 - 153*

Presenter's Notes: Two points can be made:

1. The REE is higher in the coal itself than it is in the clay partings.
2. The lower bench appears (below the partings) appears to have some "zones" of higher concentration value than is found in the upper bench.

For this coal, the lower bench was often left unmined due to its high ash content.