



Recovery of Rare Earth Elements (REEs) from Coal Mine Drainage

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West Virginia Coal Association
Income Opportunities from Reclaimed Mine Land
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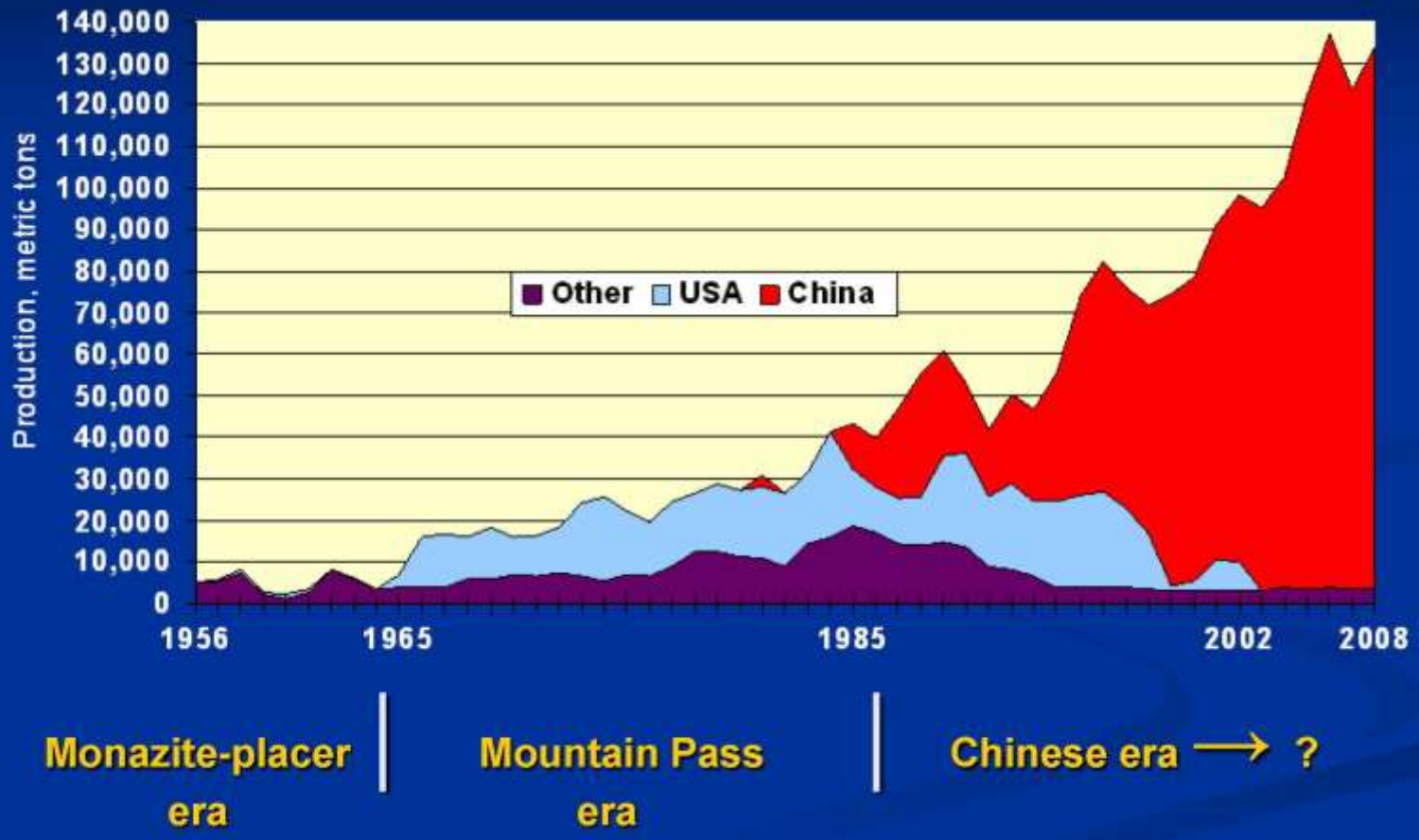
WestVirginiaUniversity

REE: RESOURCE CHARACTERIZATION

- Demand
- Project Strategy
- Feedstock
  - Acid mine drainage
  - Treatment
  - AMD precipitates
    - Quality
    - Quantity

Our strategic disadvantage: China controls exports ~ 35kt/yr



USGS

Projected TREE demand through 2025 (tons/year)

	Global demand @ 7% ann. Growth	USA demand total*	USA demand defense**
2017	158,403	15,840	792
2018	169,845	16,984	849
2019	182,176	18,218	911
2020	195,469	19,547	977
2021	209,804	20,980	1,049
2022	225,265	22,527	1,126
2023	241,947	24,195	1,210
2024	259,951	25,995	1,300
2025	279,387	27,939	1,397

? ?

* 10% global

** 5% USA demand

This assumes that USA manufacturing demand does not increase beyond current rates

USDOE Funded REE research at WVU

Phase 1.

1. Development of a cost-effective & environmentally benign process to treat and recover REEs from AMD
2. Preliminary process system design and techno-economic analysis in preparation for pilot-scale testing
3. Down select by USDOE/NETL

Phase 2.

1. Build and operate a pilot plant
2. Report cost/performance

Participants

WVU

- Paul Ziemkiewicz, PhD
  - Director, WVU Water Research Institute
- Xingbo Liu, PhD
  - Professor, Mechanical and Aerospace Engineering
- Aaron Noble, PhD
  - Assistant Professor, Mining Engineering

External

- Mepco Inc.
- Rosebud Mining Co.
- West Virginia Dept. of Environmental Protection
- Alliance Coal Corp.
- Consol Energy, Inc.
- Rockwell Automation

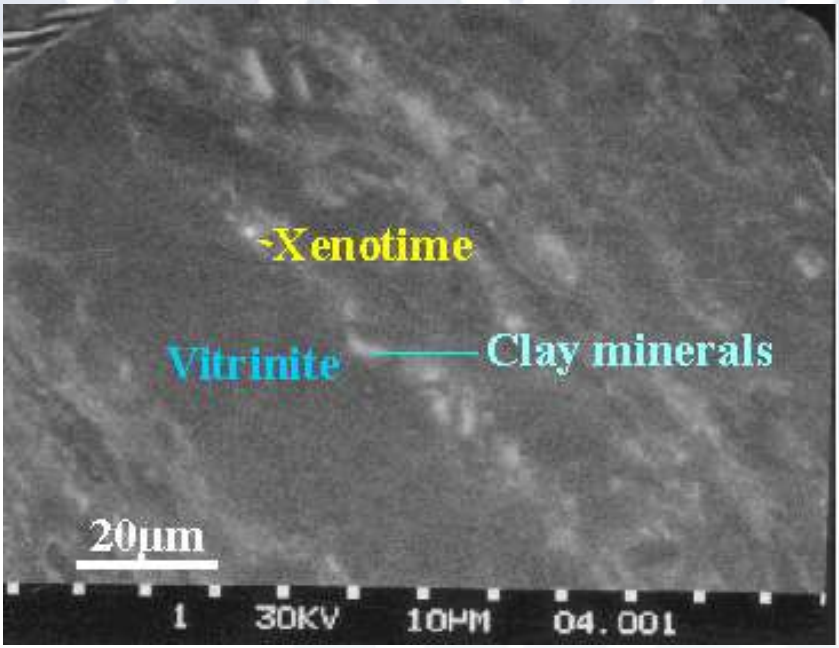
Objective: Develop new, sustainable market-driven opportunities around domestic REE sources

Important criteria for attracting investment

- Size of the resource
- Market valuation
- Development costs
  - Preliminaries: exploration, planning, site development…
  - capX
  - opX
- Technology readiness (TRL)
- Environmental footprint
  - permitting
  - liabilities

Mineral associations in WV coals
from WVGES

- Monazite (less commonly xenotime): REE (PO_4 SiO_4) weathered from granite as micron-sized particles
- Does not dissolve in weak acid, requires concentrated acid to liberate REEs
- When burned in a PC boiler all of the inert minerals fuse into alumino-silicate glass
- Which is even more Resistant to acid attack

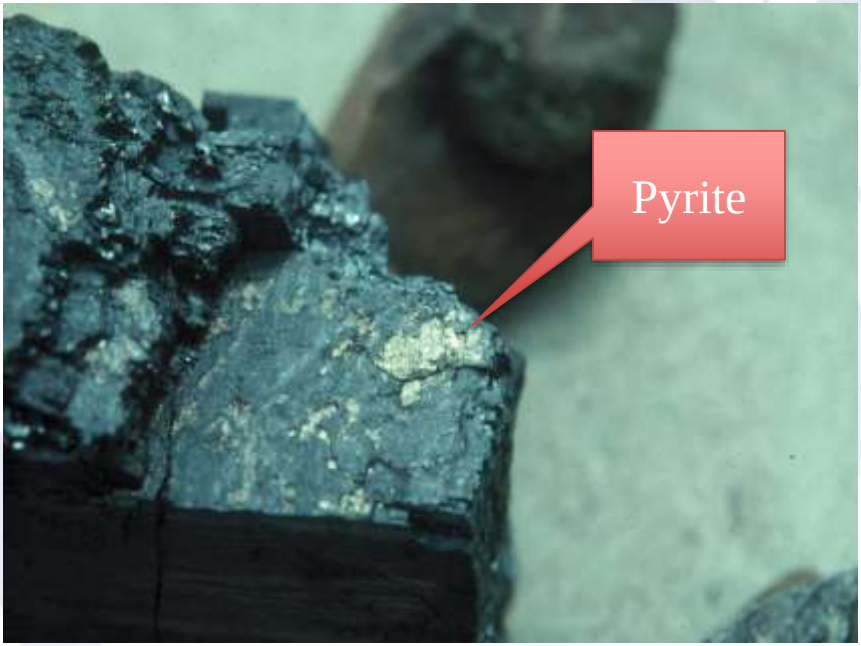


Acid Mine Drainage: AMD

1. H_2SO_4 leaches REEs from shale
2. REE's precipitate with $Fe(OH)_3$

Pyrite + O_2 + H_2O
= Fe^{2+} + H_2SO_4

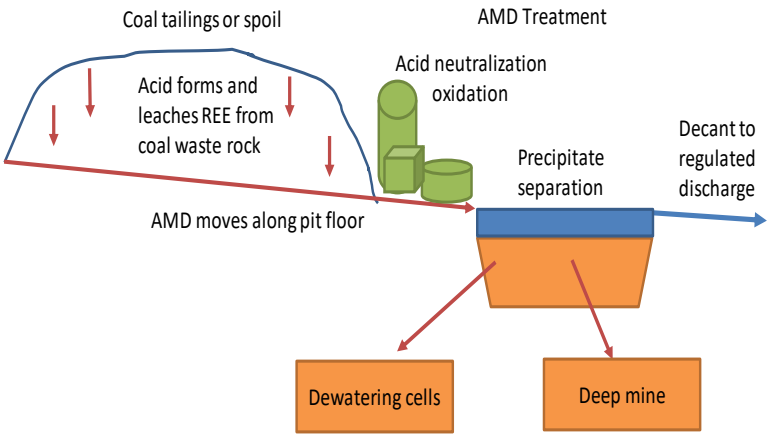
Fe^{2+} + O_2 + OH^-
= $Fe(OH)_3$



AMD sludge, Why We Care

- Inherent value: $225/kg of mixed Rare Earth oxide
- In-situ Rare Earth value of $96/t AMD sludge DW
- Refining cost = $65/t: estimated profit = $30/t
- 61% (dry weight) are the more valuable critical and heavy Rare Earth Elements
- We estimate that a commercial refinery would recover its CapX and OpX within 2.5 years

Typical AMD treatment and sludge handling



AMD sludge dewatering cell in Central WV
In-situ value = $1.3 million

AMD treatment

2. Lime for pH adjustment

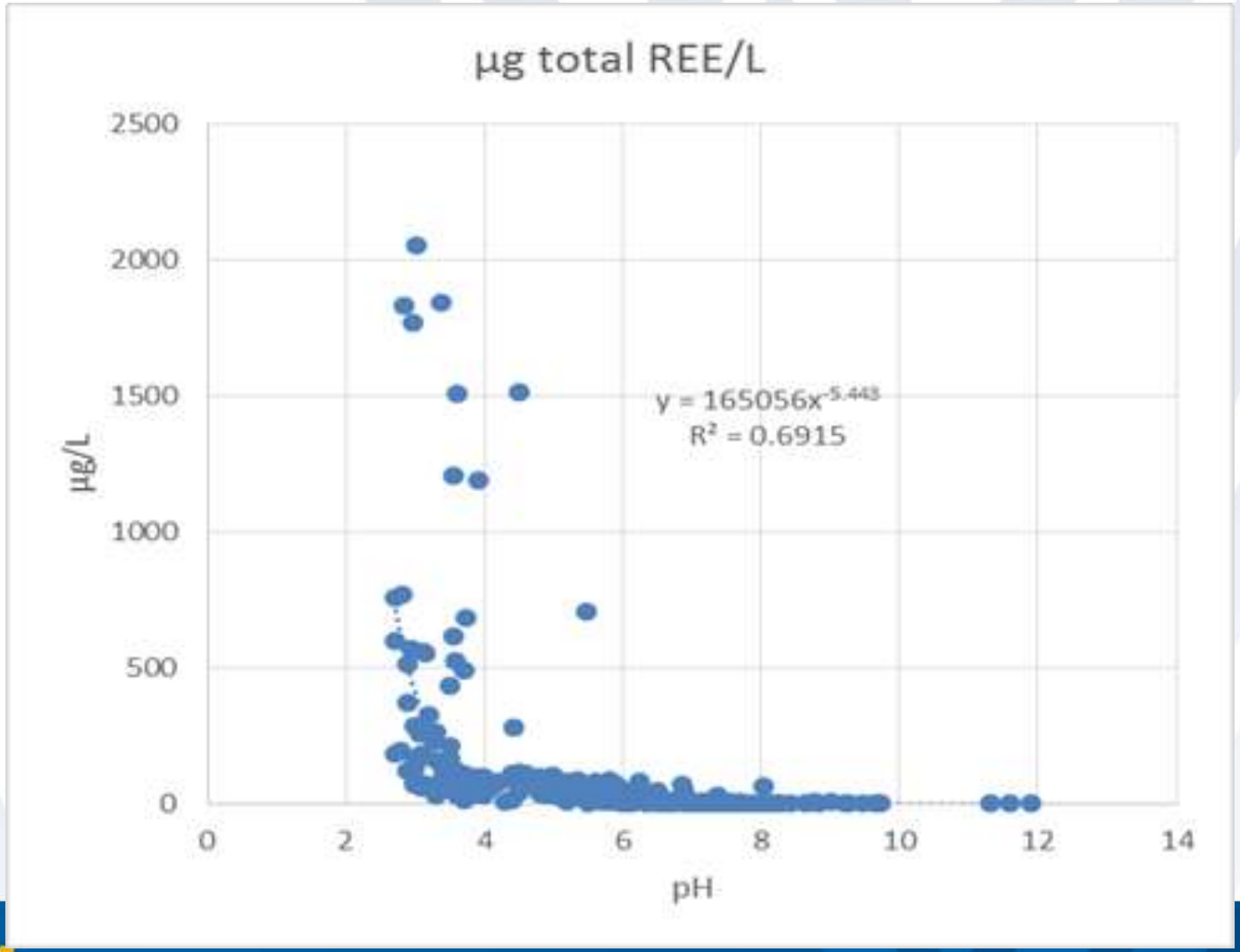
1. RAW AMD= **water** + major ions (Ss) + TREE

3. AMD treatment: lime mixing/oxidation

5. Treated **water** for surface discharge

4. AMD sludge: precipitation of major ions (Ss) + TREE

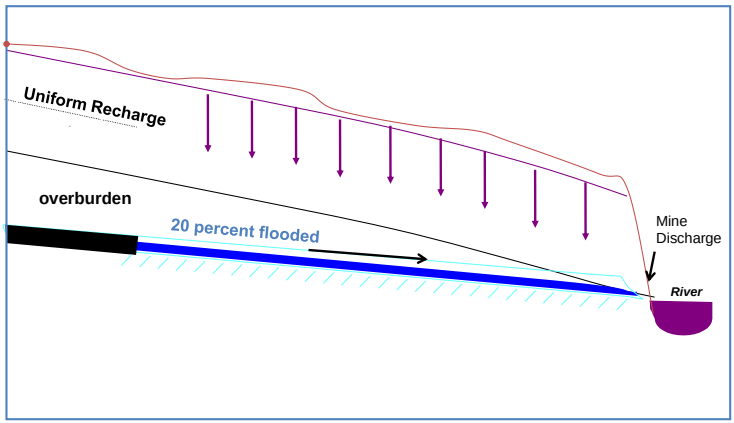
Acid mine drainage: TREE Concentration vs. raw water pH



UG mine Flooding status controls REE concentration

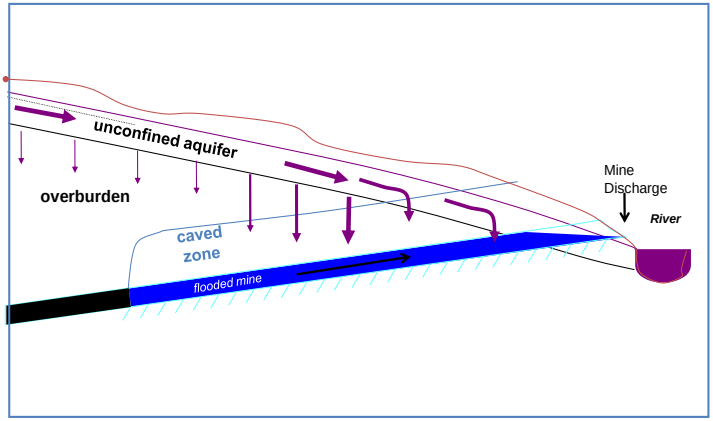
Low pH, hi REE

Unflooded, Free Draining

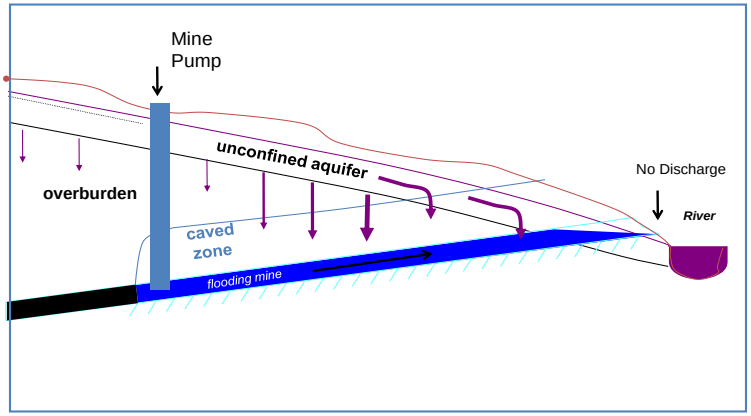


High pH, low REE

Flooded High Dilution



Flooded Mine Low Dilution



Heavy REEs are *generally* more valuable than light

Rare Earth Elements

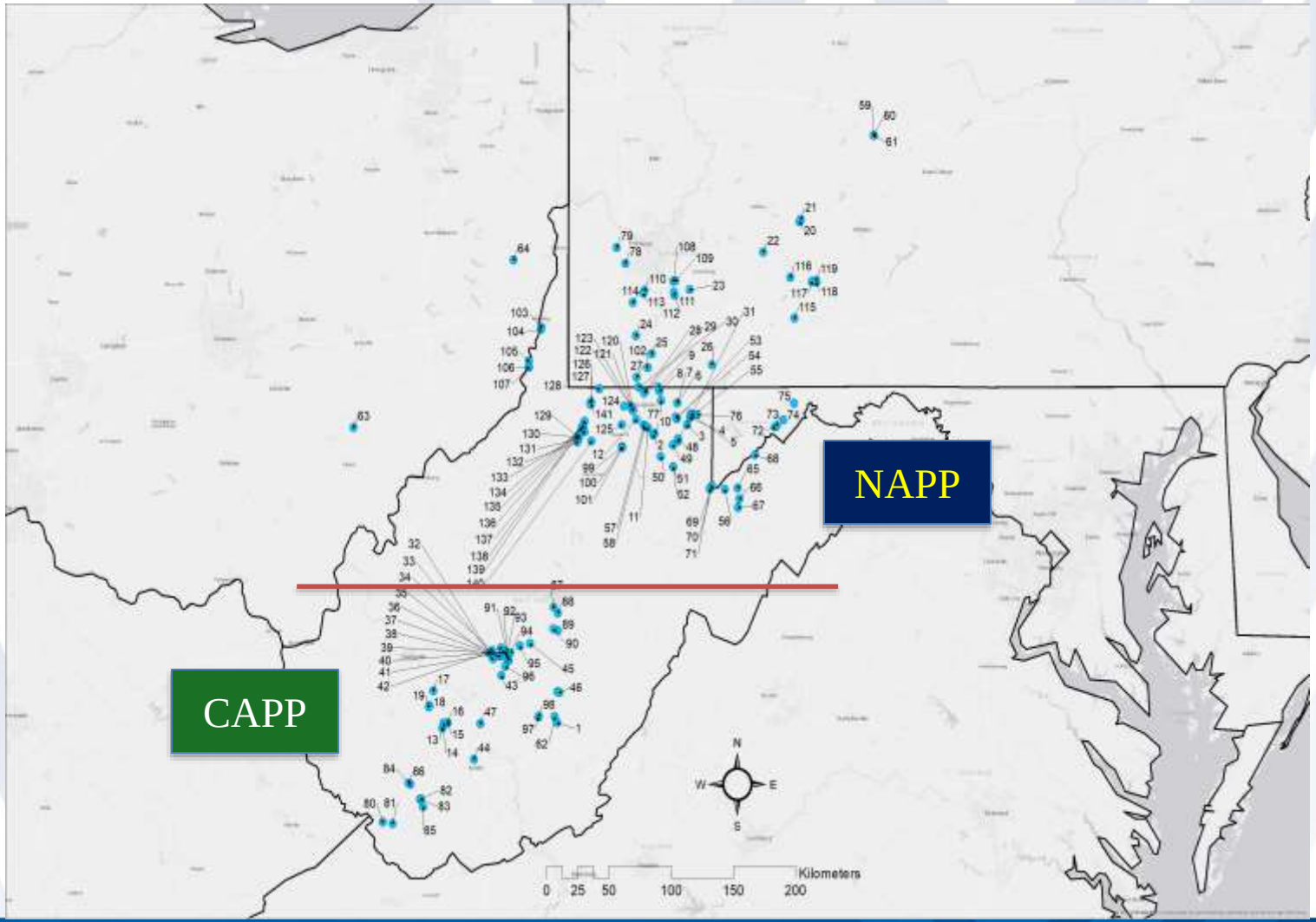
Light
Heavy

Critical
*Unstable

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	**Y**	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

Ce	Pr	**Nd**	Pm*	Sm	**Eu**	Gd	**Tb**	**Dy**	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pt	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Sampled locations: 140



CAPP VS. NAPP:

Little difference between REE distribution or total concentration (g/t)

Sites sampled:

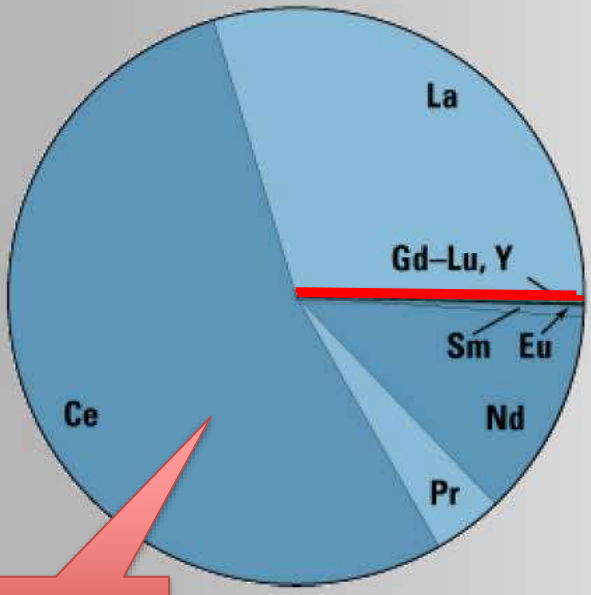
CAPP	42
NAPP	110

	CAPP	NAPP	All
La	41.4	38.4	39.9
Ce	97.1	95.0	96.0
Pr	14.4	14.0	14.2
Nd	66.5	64.5	65.5
Sm	18.2	17.6	17.9
Eu	4.4	4.5	4.4
Sc	12.8	14.9	13.8
Y	88.6	108.7	98.7
Gd	23.9	24.3	24.1
Tb	3.4	3.7	3.6
Dy	18.8	20.7	19.8
Ho	3.5	4.0	3.8
Er	9.1	10.7	9.9
Tm	1.0	1.4	1.2
Yb	6.7	8.1	7.4
Lu	0.9	1.2	1.0
TREE	410.6	431.6	421.1

Distribution of HREE in AMD sludge is similar to south China clays

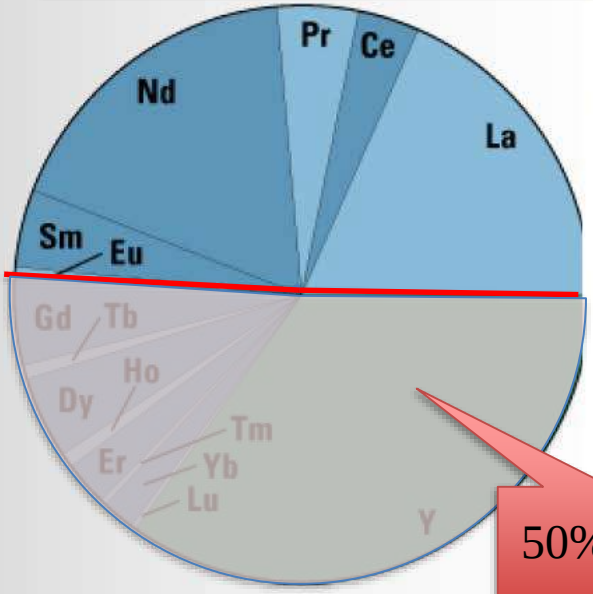
Relative proportions of REE in carbonatites vs laterites

Bayan Obo, Mountain Pass



almost all LREE

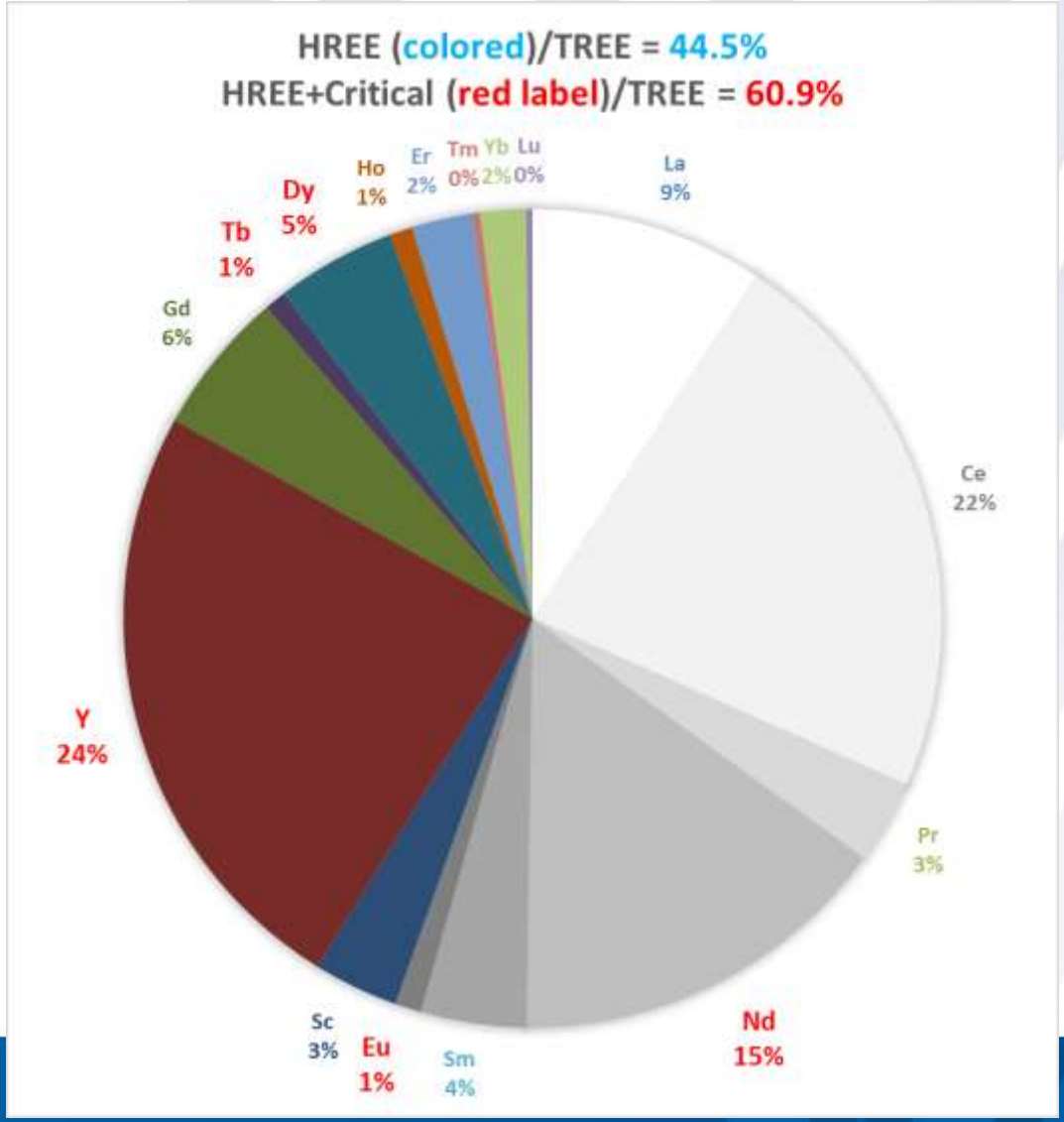
South China Clay



50% HREE - Sc

USGS facts sheets

Heavy and Critical REEs n=155
% dry weight



REE concentrations and weighted in situ value (n=155). LREE HREE Critical Scandium represents 91% of weighted value.

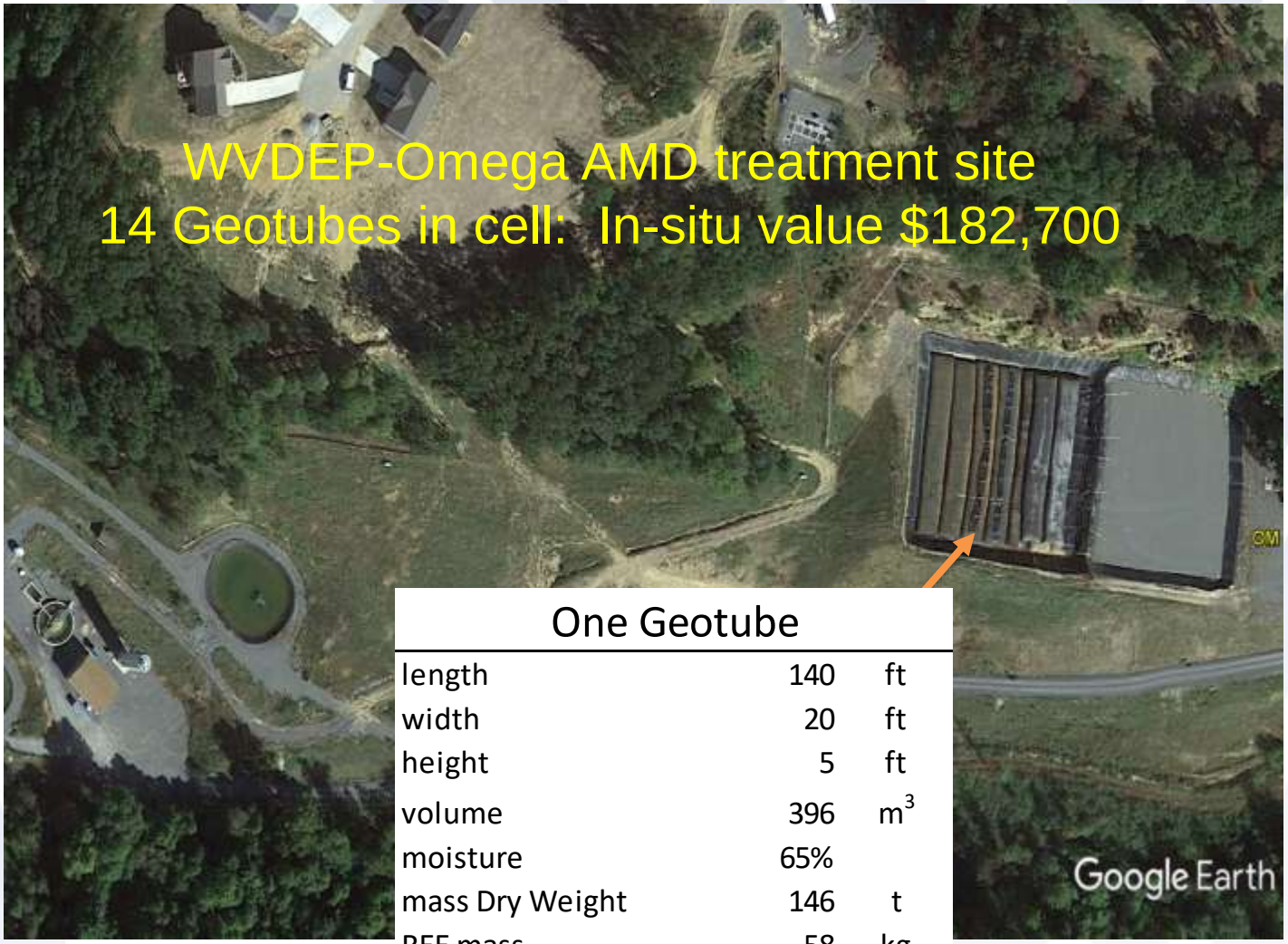
	TREE g/t DW	% TREE	$/kg elemental	weighted value $/kg TREE
La	39.2	9.2%	$ 7.00	$ 0.65
Ce	95.6	22.4%	$ 7.00	$ 1.57
Pr	14.1	3.3%	$ 85.00	$ 2.81
Nd	65.0	15.3%	$ 60.00	$ 9.16
Sm	17.8	4.2%	$ 7.00	$ 0.29
Eu	4.4	1.0%	$ 150.00	$ 1.57
Sc	14.3	3.4%	$ 15,000.00	$ 504.32
Y	103.3	24.2%	$ 35.00	$ 8.49
Gd	24.2	5.7%	$ 55.00	$ 3.12
Tb	3.6	0.9%	$ 550.00	$ 4.68
Dy	20.2	4.7%	$ 350.00	$ 16.62
Ho	3.9	0.9%		
Er	10.2	2.4%	$ 95.00	$ 2.28
Tm	1.3	0.3%		
Yb	7.7	1.8%		
Lu	1.1	0.3%		
sum	425.9			$ 555.56

metal value

In situ sludge value=market value of REEs excluding transport and processing

Small AMD sludge drying cell
0.5 ac, 10 ft deep, 80% moisture
Sludge DW 1,300 t
$190/ton of sludge DW
In situ REE value = **$247,000**

Accessibility/extractability/dewatering



One Geotube			
length		140	ft
width		20	ft
height		5	ft
volume		396	m^3
moisture		65%	
mass Dry Weight		146	t
REE mass		58	kg
in-situ value	$	225	/ kg
in-situ value	$	13,050	

Estimated REE production CAPP/NAPP 155 sites

Sludge cells sampled to date:		**155**	
Sludge		2,344,452	m^3
solids content		21%	
Sludge		519,413	tons DW
average TREE grade		419.1	g/t
TREE		217,686	kg
in-situ value	$	225.00	/kg TREE
in-situ TREE value	$	48,979,379	

All Sites	Units	Sampled sites (n=140)	est. total APP[1]	est. total APP[2]
Total Q	L/sec	6,221	94,838	418,000
% total APP Q			6.56%	1.49%
Total TREE flux	kg/year	41,395	631,059	2,781,412
In-situ value/year	@ $225/kg TREE	9,313,905	141,988,220	625,817,729

[1]APP basin AMD discharge (Q) per this study

[2]APP basin AMD discharge (Q) per Stewart et al., 2017

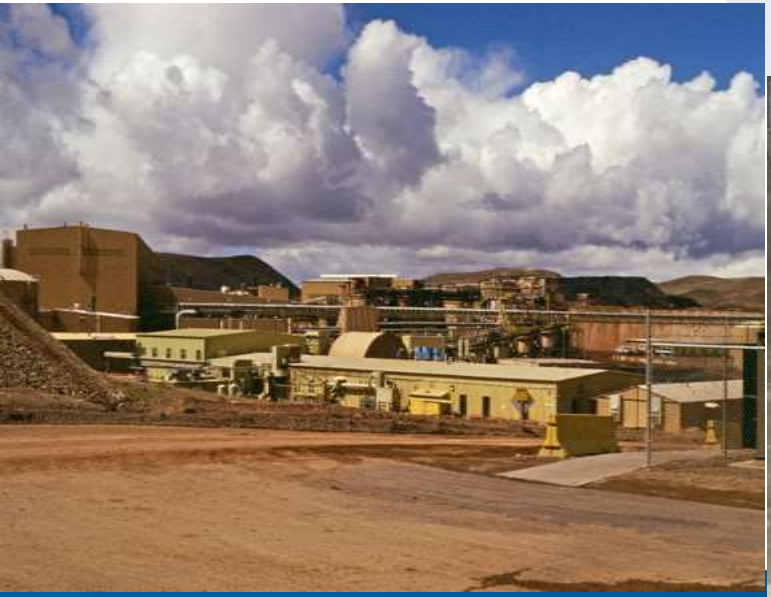
Next Step: Refine and separate REEs to commercial grades

REE Recovery

1. Acid Leaching
2. Solvent Extraction
3. Economics

Gold mine near Battle Mt., NV

Ore processed at its acid heap leach and solvent extraction plant



Revenue potential: two scenarios

(we are in the early stages of optimizing the modular plant)

Parameter	modular plant 6.25 t/hr	Centralized plant 2100 t/day
sludge feed grade	425 g/t, 65% moisture	
overall process recovery	87.20%	
weighted average metal quotation	$225/kg REE	
inherent value	$96/t plant feed	
realization	$6100/t concentrate	
REE concentrate production	1.36 t/day	29 t/day
internal rate of return	10%	46%
payback period (operating years)	**18.5 years**	**2.5 years**
Net present value (1=10%)	$ 47,217	$ 63,454,000

Questions?

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