In response to Governor's Executive Order 25-62

INDIANA'S OPPORTUNITY IN RARE EARTH ELEMENTS AND CRITICAL MINERALS

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A deposit of coal preparation plant waste in Pike County, 2023. | Maria Mastalerz, IGWS photo

Indiana's Opportunity in Rare Earth Elements and Critical Minerals

(executive summary bullet points)

Introduction

Rare earth elements (REEs) and other critical minerals (CMs) power nearly every advanced technology—from electric vehicles and wind turbines to medical imaging and defense systems. Yet, 60-70% of the global REE production and 90% of global REE separation and processing occurs in China, creating a major supply chain risk. Indiana's coal legacy means the state holds billions in untapped critical materials locked in coal, paleosols, coal ash, mine and coal preparation plant refuse, acid mine drainage, and shale formations. This report provides evaluation of potential sources of REE-CM in Indiana, their quantity and quality, with the implications for potential mineral recovery. Current REE-CM extraction methods are discussed, with the emphasis on the element recovery from low-grade feedstock. Technological and economic viability of the potential recovery is discussed based on available data from laboratory experiments and pilot-scale projects in the US and worldwide, whereas environmental considerations are discussed within the framework of the current Indiana regulations.

Key findings

- Indiana's coal ash, coal refuse, and acid mine drainage all are potential sources of REEs and other critical minerals such as gallium and germanium. The concentration of these elements exceeds those in the original coal and compares favorably to similar U.S. and world coal-based materials.
- Coal ash stored in Indiana's impoundments could contain over $5.0B in recoverable REEs , and approximately $5.8B is locked in the coal refuse. Acid mine drainage provides additional opportunities. Existing coal preparation plants and coal-fired power plants (~5M tons/year) add additional value in potentially recoverable critical minerals.
- Proven recovery technologies exist, with up to 90% REE recovery. However, considering low concentrations of REE in coal-based waste material and their complex phase associations, the recovery of REEs and other critical elements from these materials will be a multi-staged process, requiring well-designed pre-concentration phase as well as elaborate leaching and purification.
- Reusing waste reduces environmental liability. Indiana already maintains a strong regulatory framework for coal refuse and coal combustion residuals, but new rules or rule modifications and regulatory clarity might be needed related to REE-CM recovery to assure the protection of the environment.

Challenges

- Recovery of REE-CM from Indiana coal-based material will be costly, improvements in the recovery process need to be made, and other options (co-production, beneficial use of post-recovery waste) need to be considered to make the recovery process economically viable.
- Comprehensive techno-economic assessments of REE-CM recovery projects of Indiana resources can only be possible if large-scale projects are established and they yield suitable data for robust analysis.
- High startup and permitting uncertainty limit private investment. It may also discourage operators from pursuing REE-CM recovery projects.
- Current environmental regulations govern coal mining and waste disposal, but not resource recovery. Because there are no large-scale REE-CM recovery facilities available to inform what regulations will be needed, the scale of changes in regulations is difficult to predict.
- With a lot of environmental concerns about the coal waste disposal, public perception of risk versus benefits related to the waste processing need to be evaluated.

Next steps for Indiana

- Launch 2–3 pilot recovery projects (coal ash, AMD, refuse) with environmental monitoring.
- Create a public–private REE Consortium (IGWS, IU, Purdue, IDEM, industry).
- Offer tax credits and pursue DOE/DOD matching funds.
- Develop a one-stop permitting office and clear IDEM/IDNR guidance.
- Integrate REE recovery into Indiana's energy and economic plans.

The Bottom Line

Indiana can turn legacy coal waste into a strategic clean-tech asset. With pilot projects, clear rules, and public-private collaboration, the state can lead the nation in securing critical minerals while supporting jobs, innovation, and energy security.

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Indiana's Opportunity in Rare Earth Elements and Critical Minerals

In accordance with Indiana Gov. Mike Braun's Executive Order 25-62

SUMMARY

Rare earth elements (REEs) and other critical minerals (CMs) underpin modern energy, defense, and advanced manufacturing systems. They are essential for technologies ranging from electric vehicle batteries to medical equipment, magnets, ceramics, catalytic converters, jet engines, and renewable energy systems. Yet, the United States relies heavily on imports: 70% of rare-earth compounds and metals between 2020 and 2024 came from China; China also controls nearly 90% of the global processing capacity. This geopolitical concentration creates a strategic vulnerability. Indiana, with its long history of coal mining and energy production, holds significant potential to reduce that dependence by recovering REEs and CMs from unconventional sources such as coal refuse, coal ash, acid mine drainage (AMD), paleosols, and metalliferous shales.

Our assessment shows that Indiana's coal-based materials already meet or exceed benchmarks for REE enrichment. Coal refuse from the Springfield Coal Member, Danville Coal Member, and other economically important coal members contains REE, yttrium, and scandium at levels comparable to U.S. averages, while abundant coal ash produced by Indiana coal-fired power plants (~5 million tons annually) offers even higher enrichment. Pilot studies conducted in the U.S show that roasting coal ash with sodium hydroxide (NaOH) followed by acid leaching can recover more than 90% of REEs. By our estimates, Indiana's coal ash impoundments alone hold more than $5.8 billion in recoverable REEs, with scandium accounting for the largest share due to its exceptionally high price. Coal preparation plant refuse, AMD, and paleosols add further opportunities, with AMD already generating concentrated precipitates as part of mandated remediation, and paleosols containing gallium at levels above industrial thresholds.

Recovery methods are technically feasible but vary in cost and complexity. Physical beneficiation—density, magnetic, and flotation separation—can preconcentrate feedstocks, but so far offers only modest gains. Metallurgical pre-treatment through pyrometallurgy and hydrometallurgy is more effective, particularly for converting difficult-to-leach coal ash into soluble oxides. Acid leaching, often combined with thermal or alkali pretreatment, is the most widely studied approach, while new technologies such as solvometallurgy, membrane separation, and microbial recovery show promise but remain at early stages of development. Technologically successful projects will likely require hybrid approaches that combine proven industrial methods with the selective adoption of emerging techniques.

Environmental and regulatory frameworks function as both constraints and opportunities. Indiana already has rules for coal refuse reclamation under the Surface Mining Control and Reclamation Act (SMCRA) and the Abandoned Mine Lands (AML) Program, and for coal ash disposal shaped by the U.S. Environmental Protection Agency's (EPA's) Coal Combustion Residuals (CCR) Rule. Utilizing coal waste streams for REE-CM recovery will raise new questions—neutralizing leachates, handling residues, and ensuring groundwater protection—but could also mitigate legacy risks by reducing the volume of coal waste and AMD sludge. Current rules, however, were written for waste disposal and management, not mineral recovery, which means new regulations or incentives may be needed to support safe, beneficial use.

In sum, Indiana holds a significant underutilized resource base for critical minerals, with billions of dollars in potential value and a direct role in U.S. supply chain security. Realizing this opportunity will depend on three factors: lowering processing costs through pre-concentration and co-production of other valuable metals (e.g., gallium, germanium, vanadium); developing industrial-scale pilot projects to validate recovery methods; and aligning state and federal policy to encourage investment while maintaining strong environmental safeguards. With targeted support, Indiana could move from being a legacy coal producer to a leader in securing critical minerals for the U.S. economy.

1. INTRODUCTION

Awareness of rare earth elements (REEs) and other critical materials (CMs) has surged in recent years as their roles in energy, defense, and advanced technologies become clearer. Demand continues to rise, increasing the urgency of securing new supplies and improving recovery methods. This section provides a general overview of REEs, their classification, and their importance.

The U.S. Geological Survey (USGS) identifies dozens of minerals as critical because they are essential to technologies ranging from batteries to jet engines; yet, most are imported (Table 1; fig. 1). In turn, the U.S. Department of Energy (DOE) publishes a list of materials which are critical for energy security (fig. 2); many of these DOE critical materials are also present on the USGS's critical mineral list. REEs, divided into light and heavy groups, are particularly valuable, and China

Table 1. U.S. Geological Survey list of critical minerals and their usage (USGS, 2022a). The 2025 draft list, after the public comment and technical review stage, is (as of Dec. 12) under consideration by U.S. Department of the Interior (https://www.usgs.gov/media/images/status-2025-list-critical-minerals).

Element/Mineral	Application
Aluminum (Al)	almost all sectors of the economy
Antimony (Sb)	lead-acid batteries
Arsenic (As)	semi-conductors
Barite ($BaSO_4$)	hydrocarbon production
Beryllium (Be)	alloying agent in aerospace and defense industries
Bismuth (Bi)	medical and atomic research
Cerium Ce)	catalytic converters, ceramics, glass, metallurgy, and polishing compounds
Cesium (Cs)	research and development
Chromium (Cr)	stainless steel and other alloys
Cobalt (Co)	rechargeable batteries and superalloys
Dysprosium Dy)	permanent magnets, data storage devices, and lasers
Erbium (Er)	fiber optics, optical amplifiers, lasers, glass colorants
Europium (Eu)	phosphorus and nuclear control rods
Fluorspar (CaF_2)	manufacture of aluminum, cement, steel, gasoline, and fluorine chemicals
Gadolinium (Gd)	medical imaging, permanent magnets, and steelmaking
Gallium (Ga)	integrated circuits and optical devices like LEDs
Germanium (Ge)	fiber optics and night vision
Graphite (C)	lubricants, batteries, and fuel cells
Hafnium (Hf)	nuclear control rods, alloys, and high-temperature ceramics
Holmium (Ho)	permanent magnets, nuclear control rods, and lasers
Indium (In)	liquid crystal display screens
Iridium (Ir)	coating of anodes for electrochemical processes and as a chemical catalyst
Lanthanum (La)	catalysts, ceramics, glass, polishing compounds, metallurgy, and batteries
Lithium (Li)	rechargeable batteries
Lutetium (Lu)	scintillators for medical imaging, electronics, and some cancer therapies
Magnesium (Mg)	an alloy and for reducing metals
Manganese (Mn)	steelmaking and batteries
Neodymium (Nd)	permanent magnets, rubber catalysts, and in medical and industrial lasers
Nickel (Ni)	stainless steel, superalloys, and rechargeable batteries
Niobium (Nb)	steel and superalloys
Palladium (Pd)	catalytic converters and as a catalyst agent
Platinum (Pt)	catalytic converters

Table continued on next page

Element/Mineral	Application
Praseodymium (Pr)	permanent magnets, batteries, aerospace alloys, ceramics, and colorants
Rhodium (Rh)	catalytic converters, electrical components, and as a catalyst
Rubidium (Rb)	research and development in electronics
Ruthenium (Ru)	catalysts, as well as electrical contacts and chip resistors in computers
Samarium (Sm)	permanent magnets, as an absorber in nuclear reactors, and in cancer treatments
Scandium (Sc)	alloys, ceramics, and fuel cells
Tantalum (Ta)	electronic components, mostly capacitors and in superalloys
Tellurium (Te)	solar cells, thermoelectric devices, and as alloying additive
Terbium (Tb)	permanent magnets, fiber optics, lasers, and solid-state devices
Thulium (Tm)	various metal alloys and in lasers
Tin (Sn)	protective coatings and alloys for steel
Titanium (Ti)	a white pigment or metal alloys
Tungsten (W)	wear-resistant metals
Vanadium (V)	alloying agent for iron and steel
Ytterbium (Yb)	catalysts, scintillometers, lasers, and metallurgy
Yttrium (Y)	ceramic, catalysts, lasers, metallurgy, and phosphors
Zinc (Zn)	metallurgy to produce galvanized steel
Zirconium (Zr)	high-temperature ceramics and corrosion-resistant alloys

dominates both their production and processing (figs. 3, 4). As conventional deposits decline or are unavailable, researchers are increasingly turning to unconventional sources such as coal waste and combustion byproducts. A surge in patent activity underscores the global race to advance recovery technologies (fig. 5).

Against this backdrop, Indiana's Executive Order 25-62 calls for a focused evaluation of the state's REE-CM potential, extraction methods, and regulatory framework—part of the broader U.S. effort to reduce dependence on China and secure resilient supply chains.

The rare earth elements (REEs) are a group of 15 lanthanides plus scandium (Sc) and yttrium (Y) (fig. 3), collectively referred to as REEs in this report. They share similar geochemical properties and are often found together in geologic formations. Based on the atomic number, they are divided into the light or cerium group (LREE, elements 57 to 63), and the heavy group, known also as the yttrium group (HREE, elements 64 to 71) (fig. 3). Heavy REEs are less common, which typically makes them more desired and more expensive. REEs are also often referred to as "rare earth oxides" because they are typically sold as oxide compounds (Balaram, 2019; King, 2021; Mastalerz and others, 2020; Drobniak and Mastalerz, 2022).

Igneous and metamorphic rocks are the traditional sources of REEs, but sedimentary rocks have also become of interest as demand grows. While more than 250 minerals can contain REEs, economic-scale concentrations of rare earths are primarily found in carbonatites, alkaline igneous systems, ion-absorption clay deposits, and monazite-xenotime-bearing placer deposits. Because of the depletion of these primary sources and because of the fact that the current REEs production is dominated by China (fig. 4), other countries, including the United States, direct their attention toward other potential REE sources like coal mining waste and coal combustion byproducts, which could potentially supply a significant amount of REEs in many coal-mining countries (DOE, 2022; Mastalerz and others, 2020). The international interest in other potential sources of REE-CM has been documented by countless studies from laboratory to pilot-scale projects worldwide; the drive toward improving recovery on techniques can be expressed by the growing number of patents related to their extraction (fig. 5). Interestingly, the trend of the patents follows that of REE production (fig. 4).

The United States relies heavily on imports of critical minerals (fig. 1) and, because of the nation's growing demand, identifying new domestic sources that could be recovered economically is an important and challenging, yet very timely task. In accordance with Indiana Executive Order 25-62, this report characterizes possible sources of REE-CM in Indiana, reviews extraction techniques, and discusses environmental and feasibility considerations in the context of Indiana regulations.

Critical mineral	United States					World			
	Primary production	Secondary production	Apparent consumption	Net import reliance as a percentage of apparent consumption	Primary import source (2020–23)	Leading producing country	Production in leading country	Percentage of world total	World production total
Aluminum (metallurgical grade bauxite)	—	—	[2]1,800,000	>75	Jamaica	Guinea	130,000,000	29	[3]450,000,000
Antimony	—	3,500	24,000	85	China[4]	China	60,000	60	100,000
Arsenic	—	NA	[5]9,100	100	China[4]	Peru	[6]27,000	47	[6]58,000
Barite	W	—	W	>75	India	India	2,600,000	32	[3]8,200,000
Beryllium	180	NA	170	E	Kazakhstan	United States	180	50	360
Bismuth[7]	—	80	760	89	China[4]	China	13,000	81	16,000
Chromium	—	100,000	440,000	77	South Africa	South Africa	21,000,000	45	47,000,000
Cobalt	300	2,000	8,500	76	Norway	Congo (Kinshasa)	220,000	76	290,000
Fluorspar	NA	—	430,000	100	Mexico	China	5,900,000	62	9,500,000
Gallium	—	—	[2]19	100	Japan	China	750	99	760
Germanium[7]	—	NA	NA	>50	Belgium	China	NA	NA	NA
Graphite (natural)	—	—	52,000	100	China[4]	China	1,270,000	79	1,600,000
Indium[7]	—	—	[5]250	100	Republic of Korea	China	760	70	1,080
Lithium	W	NA	W	>50	Chile	Australia	88,000	37	[3]240,000
Magnesium[7]	—	110,000	[2]50,000	>75	Israel	China	950,000	95	[3]1,000,000
Manganese	—	—	680,000	100	Gabon	South Africa	7,400,000	37	20,000,000
Nickel	8,000	92,000	[8]180,000	48	Canada	Indonesia	2,200,000	59	3,700,000
Niobium	—	NA	8,400	100	Brazil	Brazil	100,000	91	110,000
Palladium	8	45	83	36	Russia	Russia	75	39	190
Platinum	2	8.5	71	85	South Africa	South Africa	120	71	170
Rare earths (compounds and metals)[9]	1,300	NA	6,600	80	China[4]	China	[10]270,000	69	[10]390,000
Scandium	—	—	NA	100	Japan	China	NA	NA	NA
Tantalum	—	NA	770	100	China[4]	Congo (Kinshasa)	880	42	2,100
Tellurium[7]	W	—	W	<25	Canada	China	750	77	[3]980
Tin	—	17,900	37,000	73	Peru	China	69,000	23	300,000
Titanium (metal)[7]	W	W	[3]40,000	>95	Japan	China	220,000	69	[3]320,000
Tungsten	—	W	W	>50	China[4]	China	67,000	83	81,000
Vanadium	—	8,200	14,000	40	Canada	China	70,000	70	100,000
Yttrium	NA	—	500	100	China[4]	China	NA	NA	NA
Zinc[7]	[11]220,000	([11])	820,000	73	Canada	China	4,000	33	12,000
Zirconium (ores and concentrates)	<100,000	NA	<100,000	<25	South Africa	Australia	500,000	33	1,500,000

E Net exporter. NA Not available. W Withheld to avoid disclosing company proprietary data. — Zero.

[1] Critical minerals as published in the Federal Register on February 24, 2022 (87 FR 10381). Not all critical minerals are listed here. Cesium, hafnium, iridium, rhodium, rubidium, and ruthenium are not shown because available information was inadequate to make estimates of U.S. or world production.

[2] Reported consumption.

[3] Excludes U.S. production.

[4] Includes Hong Kong.

[5] Estimated consumption.

[6] Arsenic trioxide.

[7] Refinery production.

[8] Nickel in primary metal and secondary scrap.

[9] Data include lanthanides cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, terbium, thulium, and ytterbium.

[10] Mine production of rare-earth concentrates.

[11] Primary production includes both primary and secondary metal production.

Figure 1. Estimated critical minerals statistics in 2024 (USGS, 2025). Production and consumption in metric tons.

2. GEOLOGICAL EVALUATION OF POTENTIAL SOURCES OF REE-CM

Indiana's long history of coal mining has left behind large volumes of mining byproducts, making coal and coal-based products a central focus for evaluating potential sources of rare earth elements and other critical minerals. As we will demonstrate in section 2.1, coal beds in the state contain REE, yttrium (Y), and scandium (Sc) at concentrations comparable to U.S. and world averages. Some coals—such as the Montgomery Coal Bed and Upper and Lower Block Coal Members—show elevated REE concentrations on an ash basis that exceed thresholds suggested for viable recovery, while other coal members (e.g., Springfield, Danville, and Seelyville) offer potential due to their thickness despite containing lower concentrations.

Beyond in-situ unmined coal, Indiana's extensive coal preparation and combustion history has generated large volumes of fine tailings, coarse refuse, and coal ash, which may represent promising feedstocks (section 2.2). Slurry ponds alone cover nearly 2,800 acres and contain more than 100 million cubic meters of coal refuse, and analyses show REE concentrations in some deposits approaching or exceeding recovery thresholds. Existing coal ash deposits (section 2.3) show even stronger enrichment: available REE values on Indiana samples exceeded 700–800 ppm, more than double the Department of Energy's 300 ppm economic cutoff. In addition to the existing coal ash deposits, Indiana power plants produce roughly 5 million tons of coal ash annually. These waste materials, already mined and concentrated, could provide a lower-cost, strategically important pathway for domestic REE production.

Other geologic materials also warrant attention. Pennsylvanian and Devonian black shales host critical metals such as vanadium and zinc (section 2.4),

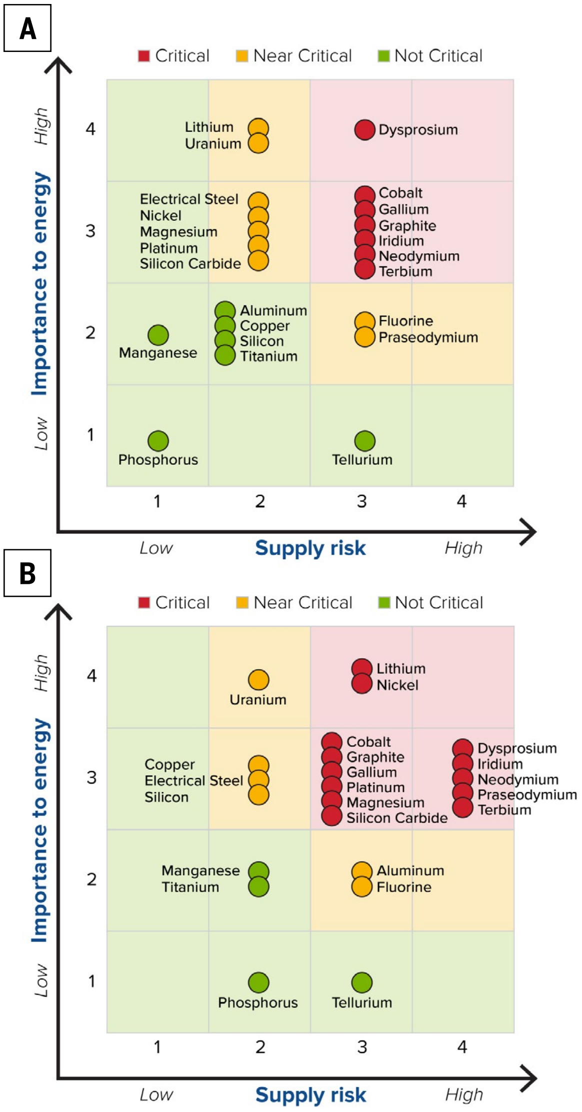


Figure 2. Criticality matrix of 2020-2025 (A) and 2025-2035 (B). Source: U.S. DOE (https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals)

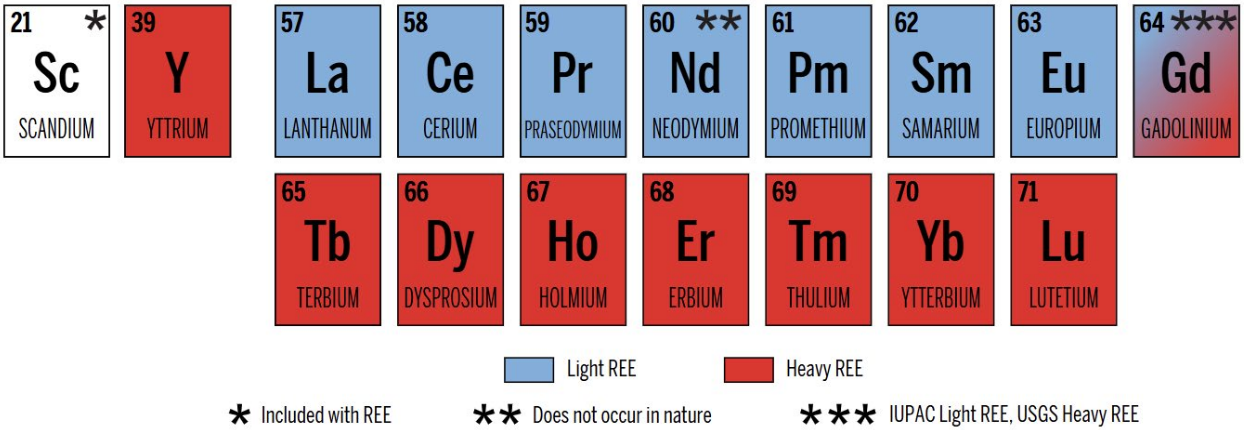


Figure 3. List and classification of rare earth elements (Mastalerz and others, 2022b).

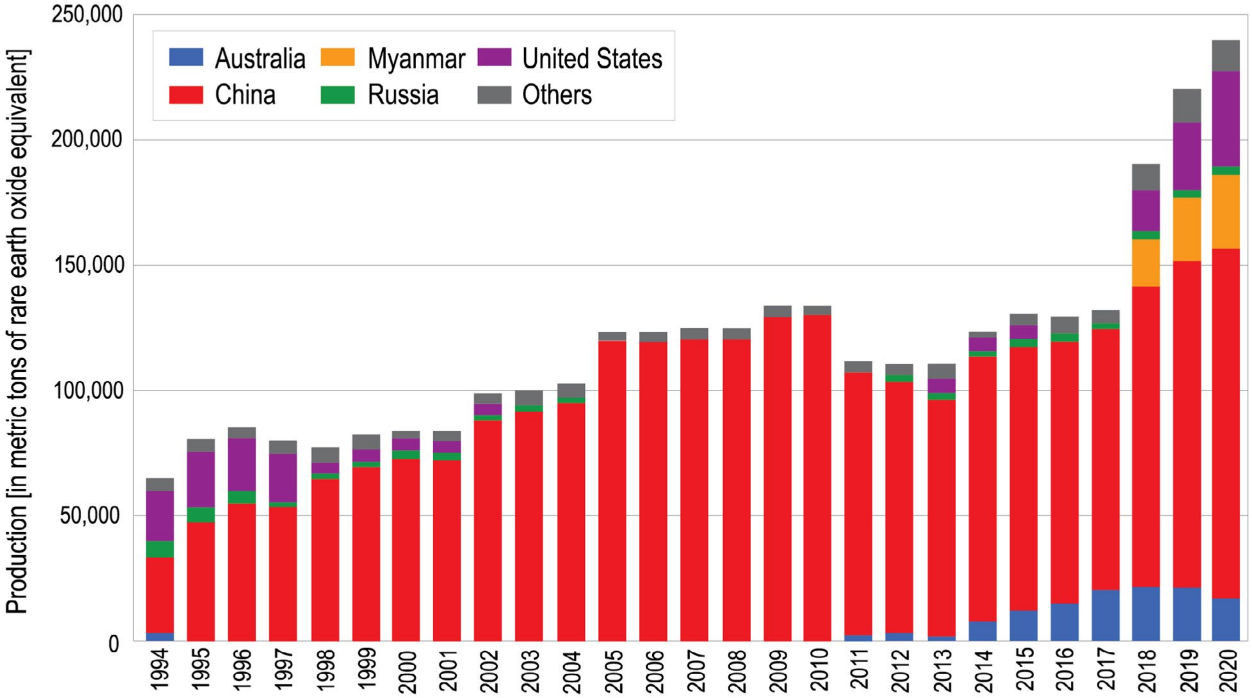


Figure 4. Bar graph showing production of REEs by country (from Drobniak and Mastalerz, 2022).

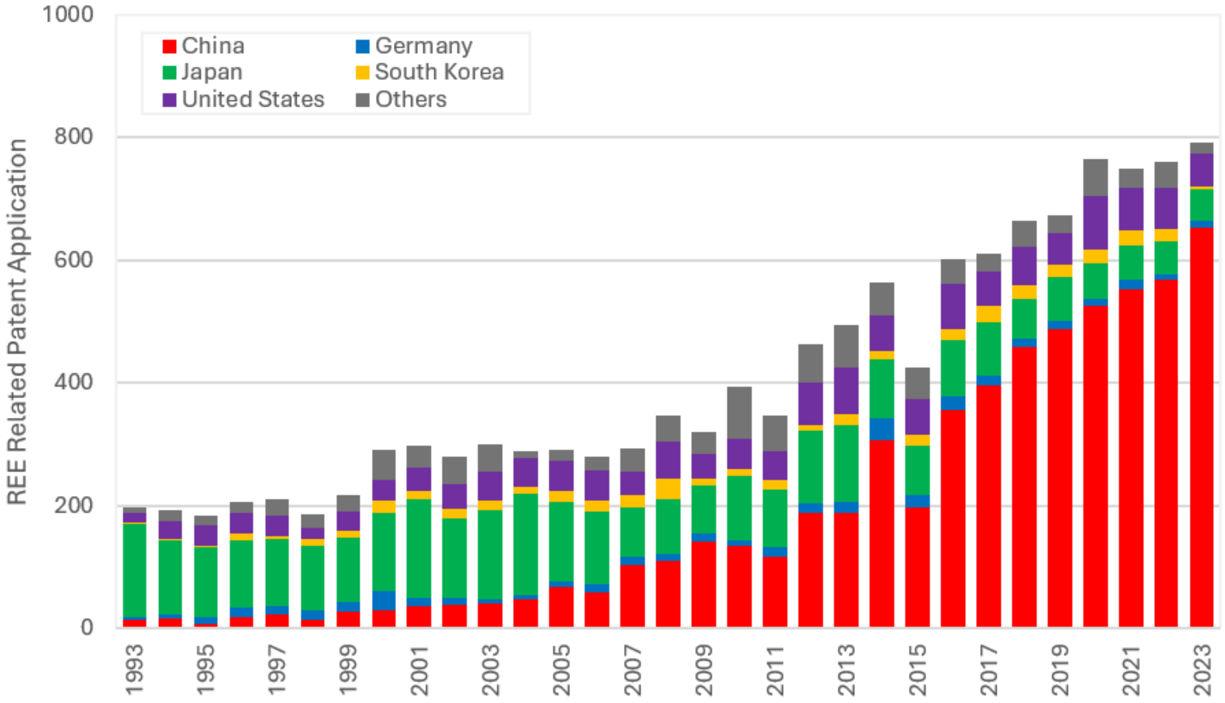


Figure 5. Bar graph showing trend in the number of patents related to REE recovery by country over past 30 years. Compiled from https://patentscope.wipo.int/search/en/result.jsf?_vid=P22-MHKU5O-72036.

while Pennsylvanian paleosols have been identified as potential sources of lithium, gallium, and germanium (section 2.5). Though paleosols generally show only moderate REE concentrations, their clay-rich character makes extraction relatively straightforward, and gallium in particular reaches levels considered commercially viable. Taken together, Indiana's coal resources, mining wastes, and associated sedimentary units position the state as a potentially significant contributor to the country's efforts to diversify critical mineral supply chains.

2.1 Coal as a source of REE-CM

2.1.1 Coal in Indiana: a brief overview

Indiana has a long history of coal mining, both underground and surface, dating back to 1880 (fig. 6). As a part of the Illinois Basin, the southwestern part of the state contains significant coal reserves of Pennsylvanian age (300–320 million years ago) (Table 2 and figs. 7–8), evaluated at ~17 billion short tons, most of that available for underground mining. The most coal still available for mining is in the Springfield Coal Member of the Petersburg Formation and the Seelyville Coal Member

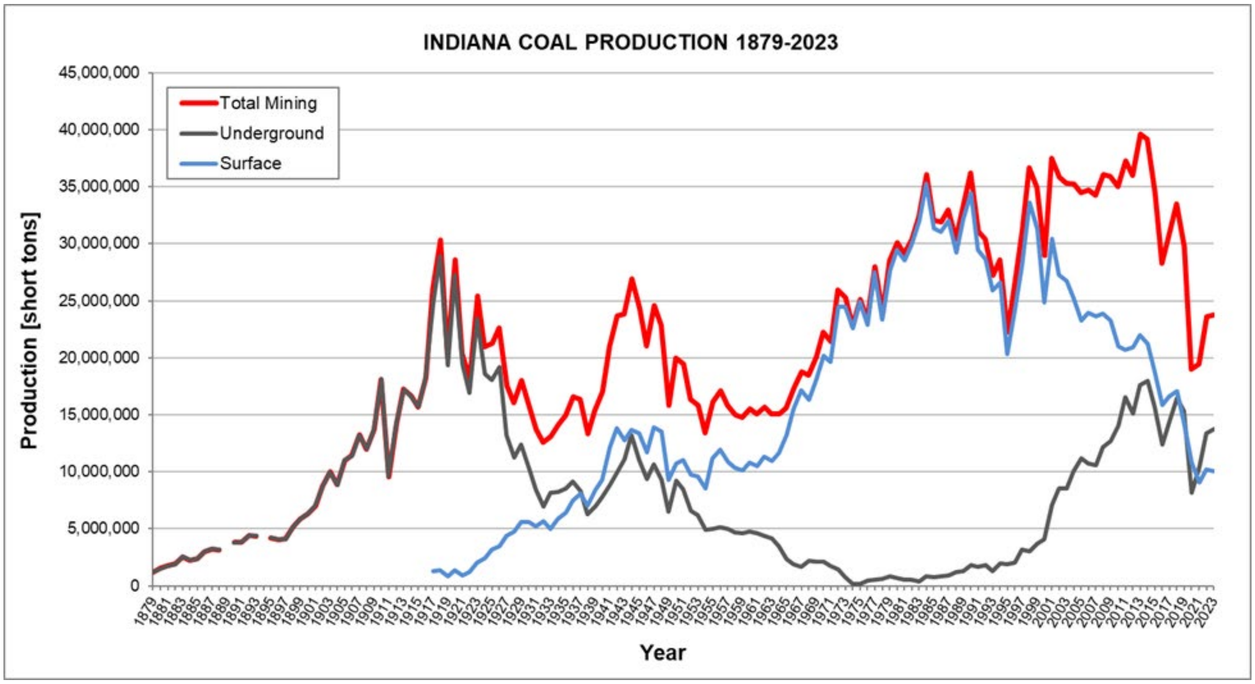


Figure 6. Line graph showing Indiana coal production through Indiana's mining history.

Table 2. Summary of available and restricted coal resources (in billion short tons) for the coal beds of most economic potential in Indiana (Mastalerz and others, 2009).

Coal bed	Original	Mined-out	Remaining	Restricted	Total available (Remaining -Restricted)	Available as % of original	Available for surface mining	Available for underground mining
Danville	6.55	0.36	6.19	5.33	0.83	13.89	0.35	0.52
Hymera	5.53	0.55	4.98	4.1	0.92	17.47	0.15	0.8
Springfield	13.31	1.31	12	4.65	7.35	61.25	0.82	6.93
Houchin Creek	5.92	0.002	5.92	5.56	0.36	6.08	0.2	0.17
Survant	8.47	0.31	8.17	6.86	1.31	16.03	0.22	1.1
Colchester	5.14	0.001	5.14	4.95	0.2	3.7	0.11	0.1
Seelyville	14.61	0.33	14.28	7.68	6.6	46.22	0.29	6.3
Total	59.53	2.86	56.68	39.13	17.57	164.64	2.14	15.92

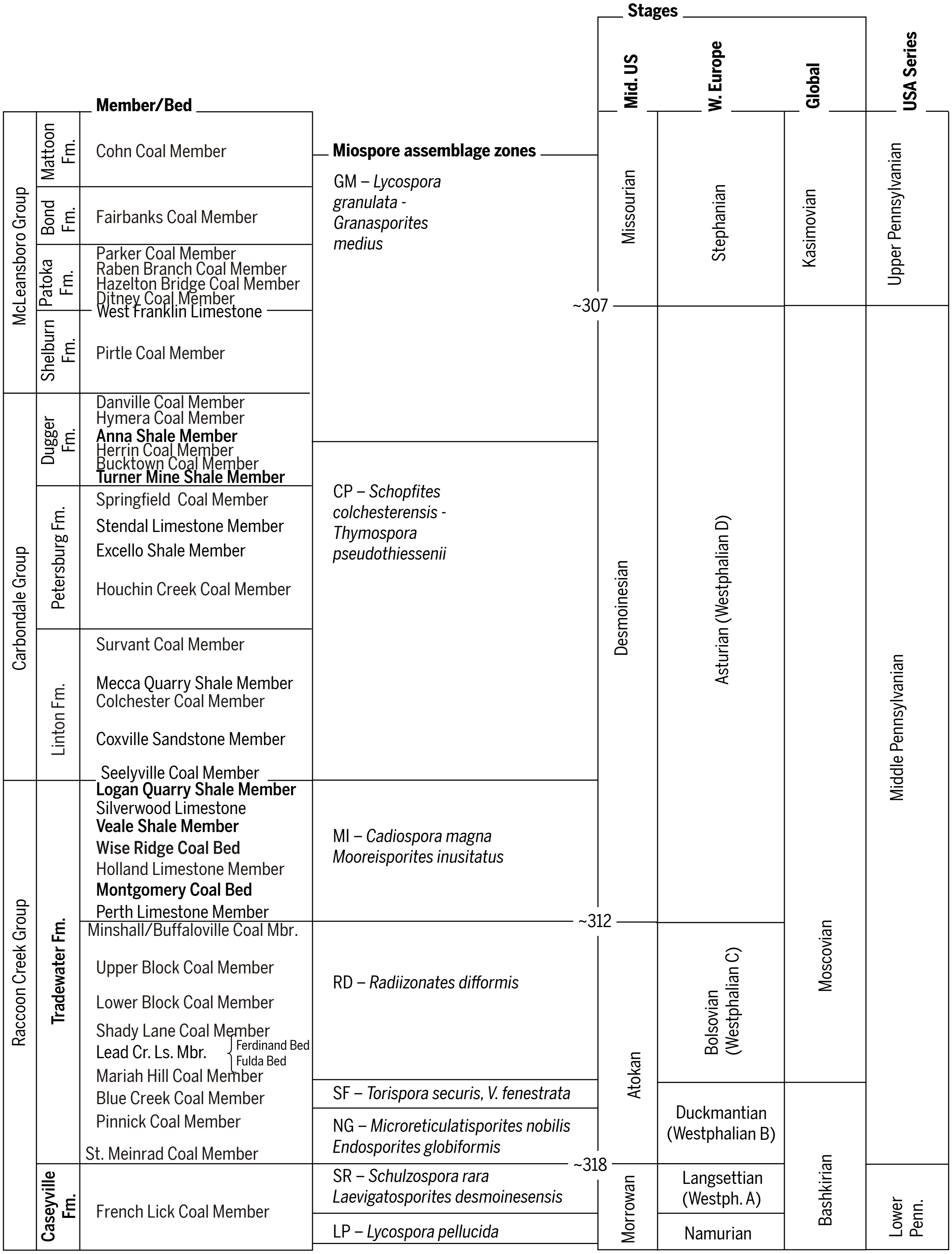


Figure 7. Stratigraphy of the Pennsylvanian in Indiana (from Mastalerz and others, 2024). Numbers refer to millions of years ago.

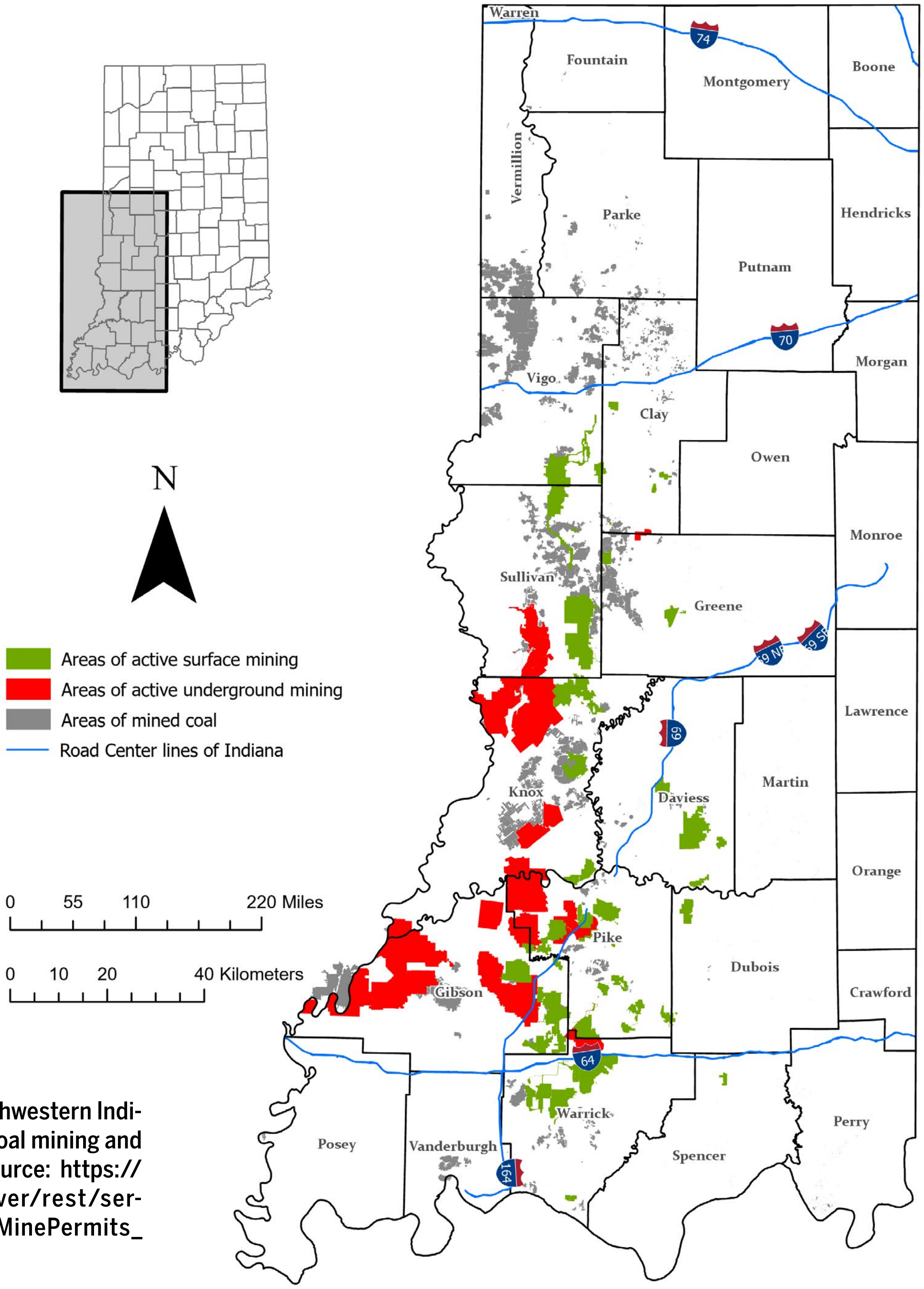


Figure 8. Map of southwestern Indiana showing active coal mining and mined-out areas. Source: https://gisdata.in.gov/server/rest/services/Hosted/CoalMinePermits_View/FeatureServer

of the Linton Formation (Table 2, fig. 7). Appendices 1 and 2 show maps of the depth and thickness of the Springfield Coal Member in Indiana.

General quality parameters of Indiana coals are summarized in Table 3. Several points should be noted when describing the quality of Indiana coals. First, although in general, Indiana coals are high in sulfur, substantial resources of the Danville Coal Member and the coals of the Tradewater Formation have low and medium sulfur contents (less than 2 %, often less than 1.5 %) and have ash contents less than 10 % (Mastalerz and others, 2009). Specifically, the Danville Coal in Knox and Sullivan Counties has low-sulfur characteristics. In Gibson County, the Springfield Coal is a low-sulfur resource, and the Lower Block Coal is a low-sulfur coal in most locations. These occurrences of low-sulfur resources set our state apart from Illinois and western Kentucky, which do not have minable low-sulfur coals. We also note that most coals in Indiana are washed and, consequently, a fraction of sulfur and other mineral matter is removed, thus improving the quality of the coal sent to customers. Previous studies (Mastalerz and Padgett, 1999; Mastalerz and others, 2009) show that a reduction in sulfur by 19 % on average and ash by 24 % on average is achieved as a result of coal washing.

Table 3. Summary of coal quality parameters for major coal beds in Indiana (Mastalerz and others, 2009). Std. dev. – standard deviation; n – number of analyses.

Parameter	Unit	Average	Std. dev.	Minimum	Maximum	n
DANVILLE COAL						
Calorific value	Btu/lb, dry	13,042	1250	7,651	17,315	252
Moisture	weight %	11.2	4.1	1.9	28.2	252
Volatile matter	weight %, dry	39.1	3.1	26.9	46.1	131
Fixed carbon	weight %, dry	48.4	4.1	32	58.2	131
Sulfur	weight %, dry	2.6	1.4	0.3	7.6	163
Ash	weight %, dry	13	4.2	4.9	41.1	254
HYMERA COAL						
Calorific value	Btu/lb, dry	12,056	1,275	2,520	13,734	135
Moisture	weight %	10.2	3.3	0.8	23.5	134
Volatile matter	weight %, dry	38.8	4.3	15.6	45.8	109
Fixed carbon	weight %, dry	46.7	5.2	11.7	54	109
Sulfur	weight %, dry	3.1	0.8	1.2	5.3	37
Ash	weight %, dry	14.5	7.8	6.8	72.7	135
SPRINGFIELD COAL						
Calorific value	Btu/lb, dry	13,211	1145.2	8,362	16,211	649
Moisture	weight %	9.9	3.8	0.5	34.7	651
Volatile matter	weight %, dry	40.9	4.3	19.9	62	306
Fixed carbon	weight %, dry	48	4.9	29	70.7	306
Sulfur	weight %, dry	3.2	1.6	0.3	7.3	420
Ash	weight %, dry	12.1	4.7	4.9	54.2	651
SURVANT COAL						
Calorific value	Btu/lb, dry	12,697	704	9,754	13,943	52
Moisture	weight %	10.4	4	1	22.2	52
Volatile matter	weight %, dry	39.7	3.6	25.2	46.9	50
Fixed carbon	weight %, dry	49.6	5	32.2	68.3	50
Sulfur	weight %, dry	3.1	0.8	1.8	5.2	19
Ash	weight %, dry	10.9	3.6	5.5	24.2	54
COLCHESTER COAL						
Calorific value	Btu/lb, dry	11,921	2,132	3,874	13,667	21
Moisture	weight %	9.9	6.4	1.9	26.9	21
Volatile matter	weight %, dry	43.4	2.7	36.9	47.4	20
Fixed carbon	weight %, dry	44.1	4.9	37.4	57.2	20
Sulfur	weight %, dry	3.1	0.4	2.8	3.4	3
Ash	weight %, dry	15.5	12.9	5.9	69.4	23
SEELYVILLE COAL						
Calorific value	Btu/lb, dry	12,211	979	8,494	13,810	83
Moisture	weight %	9.9	4.5	0.8	29.2	80
Volatile matter	weight %, dry	41.5	4.3	31.2	65.4	72
Fixed carbon	weight %, dry	44.5	5.3	19	61.1	72
Sulfur	weight %, dry	4.7	2	2.5	9.8	28
Ash	weight %, dry	14.1	5.4	6.7	35.6	85

Table continued on next page

Parameter	Unit	Average	Std. dev.	Minimum	Maximum	n
MINSHALL/BUFFALOVILLE COAL						
Calorific value	Btu/lb, dry	12,535	1,849	4,773	14,477	76
Moisture	weight %	10.2	4.2	0.7	25.8	75
Volatile matter	weight %, dry	40.4	5.4	21.3	49.9	58
Fixed carbon	weight %, dry	47.5	7.8	17.1	56.7	58
Sulfur	weight %, dry	3.7	2	1.1	11.7	40
Ash	weight %, dry	11.7	11.8	3.2	61.6	76
UPPER BLOCK COAL						
Calorific value	Btu/lb, dry	12,971	1,744	1,116	14,179	103
Moisture	weight %	14.8	5.8	1.2	52.8	103
Volatile matter	weight %, dry	38.5	3.5	26.9	47	85
Fixed carbon	weight %, dry	52.1	6.5	13.6	66.3	85
Sulfur	weight %, dry	2.1	0.9	0.6	4	54
Ash	weight %, dry	9.3	6.7	4.4	58.5	104
LOWER BLOCK COAL						
Calorific value	Btu/lb, dry	13,362	732	9,677	14,726	160
Moisture	weight %	13.6	3.5	0.7	27.1	160
Volatile matter	weight %, dry	38.6	2.8	33.5	47.5	55
Fixed carbon	weight %, dry	50.9	5.2	35.5	59.5	54
Sulfur	weight %, dry	1.3	0.8	0.56	7	124
Ash	weight %, dry	8.8	4	4.1	31	162
MARIAH HILL COAL						
Calorific value	Btu/lb, dry	12,903	707	11,109	14,182	39
Moisture	weight %	11.6	3.8	3	27.2	38
Volatile matter	weight %, dry	39.3	3	33.7	46.5	28
Fixed carbon	weight %, dry	50.5	3.2	44.7	55.7	28
Sulfur	weight %, dry	2.9	1.2	1	4.7	14
Ash	weight %, dry	9.9	3.9	3.3	20.6	38
BLUE CREEK COAL						
Calorific value	Btu/lb, dry	13,085	868	11,592	14,061	19
Moisture	weight %	13.4	3.5	7.8	21.6	19
Volatile matter	weight %, dry	38.9	2.2	35.3	44	16
Fixed carbon	weight %, dry	52.6	4.8	42.7	56.9	16
Sulfur	weight %, dry	2.8	1.5	0.7	4.5	12
Ash	weight %, dry	8.3	4.5	2.8	17.7	22

A significant proportion of Indiana coals has calorific values higher than 12,500 Btu/lb (dry basis, Table 3). These values are typical for Illinois Basin coals, and they compare favorably with western coals. A higher calorific value means that less coal must be burned to obtain a unit of energy, and this has both economic and environmental implications; less coal equals lower cost, and less coal used equals less hazardous emissions such as sulfur dioxide (SO_2), nitrogen oxide (NO_x), and mercury (Hg).

2.1.2 Rare earth elements (REEs) in Indiana coals

Data on REEs of Indiana coals come from several datasets that provide data either on whole-rock or ash basis (Mastalerz and others, 2022). On the whole-rock basis, the largest number of full-channel (covering the entire seam thickness) analyses is available for the Springfield Coal Member and the Danville and Hymera Coal Members. A brief summary of REE data on full-channel samples and on whole-rock basis for Indiana coal (Table 4) indicates that REE concentrations are similar to those found in world coals (average 68.5 ppm; Ketris and Yudovich, 2009) and in U.S. coals (62.1 ppm; Finkelman, 1993). These data also show that some coals (e.g., coals of the Tradewater Formation) consistently have higher REE concentrations compared to other coals.

Table 5 provides data for total REEs, including heavy and light REE concentrations, from two mines in Daviess County, Ind., in addition to grab samples from other mines. These values are presented on ash basis and, although they do not provide realistic values for the in-situ coal in the mines, they provide essential information about the variation of REEs between individual coal beds as well as within individual coal beds. Overall, the concentrations of REEs on ash basis in the Indiana coals vary from less than 200 ppm to more than 3,000 ppm (Mastalerz and others, 2020). The Lower Block and the Upper Block Coal Members and the Montgomery Coal Bed (Table 5) have the highest REE concentrations compared to other coals and, considering market trends, have the best commercial rare earth potential.

Experimental data related to REE extraction from the combustion waste of Russian low-rank coals suggest that combined REE oxide content above 1,000 ppm (on ash basis) could be considered the threshold for beneficial recovery of the metals (Seredin, 2004). Seredin and Dai (2012) suggested that this cut-off value could be lowered to 800 to 900 ppm, especially if the coal seam having high REE content is thick. Considering this threshold, several of the Indiana coal beds have such potential, specifically, the Montgomery Coal Bed and the Upper and Lower Block Coal Members in the Antioch and Shamrock coal mines. Considering that

Table 4. Summary of REE data on Indiana coals (full-channel raw samples, whole-rock basis) for the whole-rock-basis data set. Only samples that have the entire suite of REE data are included in this table. SD – standard deviation; light REE (La+Ce+Pr+Nd+Pm+Sm+Eu); heavy REE (Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu+Y); N – number of analyses.

Formation	Coal bed	N	Light REE [ppm]				Heavy REE [ppm]				Average total REE [ppm]
			Min	Max	Average	SD	Min	Max	Average	SD	
Dugger	Danville	13	20.8	65.7	37.5	14.2	7	16.3	11.5	2.8	48.9
	Hymera	11	15.1	87.1	40.7	25.3	4	24.7	11.8	6.3	52.5
	Bucktown	3	24.9	26.9	25.9	1	11.4	14.6	13.3	1.7	39.2
Petersburg	Springfield	31	18.4	77.5	32.8	15.6	6.2	22.5	10.4	3.1	43.3
	Houchin Creek	3	15.7	19.1	17.7	1.8	8.1	15.9	11.1	4.2	28.7
Linton	Survant	6	29.9	65.5	54.7	13.3	10.7	16	13	2	67.7
	Colchester	2	18.5	19.1	18.8	0.4	7.1	7.4	7.3	0.2	26.1
	Seelyville	5	11.5	87.6	31.7	29.2	6.1	22.5	9.5	6.5	41.1
Tradewater	Buffaloville	6	12.5	42.5	30.5	13.9	4.9	15.4	10.5	4.4	40.9
	Upper Block	10	31.3	106.9	55.8	21.3	5.1	20.3	11.5	5.1	67.3
	Lower Block	2	74.6	85.9	80.2	7.9	16.8	25.3	21	6.1	101.2
	Unnamed Block coal	13	13.1	144.1	53.2	42.8	5.1	24.2	13	5.6	66.2
	Mariah Hill	3	10.7	30.4	17.5	11.1	7.5	8.6	7.9	0.6	25.4
	Blue Creek	2	27.5	30.1	28.8	1.8	5.4	5.7	5.5	0.2	34.3
Caseyville	French Lick	6	17.5	42.9	29.6	11	3.7	10.9	7.3	2.7	36.9

Table 5. Light (LREE), heavy (HREE + Y), and total REE content in coal samples (bench and full-channel, ash basis) from Antioch Mine, Shamrock Mine, and grab samples from various coals in the Bear Run, Oaktown, and Francisco mines in Indiana. Light REE (La+Ce+Pr+Nd+Pm+Sm+Eu); heavy REE (Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu+Y).

MINE	Sample	LREE [ppm, ash basis]	HREE + Y [ppm, ash basis]	Total REE [ppm, ash basis]
ANTIOCH MINE	Wise Ridge Coal (upper bench 0–25 cm)	111.2	74.3	185.5
	Wise Ridge Coal (lower bench 25–47 cm)	99.5	117.1	216.7
	Wise Ridge Coal (full channel 0–47 cm)	105.7	94.4	200.1
	Montgomery Coal (upper bench 0–33 cm)	1,041.6	426.8	1,468.3
	Montgomery Coal (lower bench 33–59 cm)	927.1	165.9	1,093
	Montgomery Coal (full channel 0–59 cm)	991.1	311.8	1,302.9
	Buffaloville Coal (upper bench 0–8 cm)	192.1	62.5	254.6
	Buffaloville Coal (lower bench 8–16 cm)	99.4	49.3	148.7
	Buffaloville Coal (full channel 0–16 cm)	145.7	55.9	201.7
	Lower Block Coal (upper bench 0–15 cm)	168.5	150.3	318.8
	Lower Block Coal (middle bench 15–23 cm)	191.5	85.3	276.8
	Lower Block Coal (lower bench (23–35 cm)	308.2	85.8	394
	Lower Block (full channel 0–35 cm)	221.6	113.3	335
SHAMROCK MINE	Montgomery Coal (upper bench 0–14 cm)	1,199.8	107.8	1,307.6
	Montgomery Coal (middle bench 14–23 cm)	177.8	280.1	457.9
	Montgomery Coal (bottom bench 27–42 cm)	1,207.6	352	1,559.6
	Montgomery (full channel 0–42 cm)	960.8	245	1,205.8
	Buffaloville Coal (upper bench 0–17 cm)	111.1	66.8	177.9
	Buffaloville Coal (lower bench 17–43 cm)	184.9	51.4	236.3
	Buffaloville Coal (full channel 0–43 cm)	155.7	57.5	213.2
	Upper Block Coal (upper bench 0–8 cm)	173.3	170.7	344
	Upper Block Coal (middle top bench 8–12 cm)	147.6	94.4	242
	Upper Block Coal (middle lower bench 12–15 cm)	706.1	117.6	823.7
	Upper Block Coal (bottom bench 15–27 cm)	344.4	119.4	463.8
	Upper Block Coal (full channel 0–27 cm)	304.7	130.7	435.4
	Lower Block Coal (upper bench 0–20 cm)	261.8	124.2	386
	Lower Block Coal (middle bench 20–44 cm)	520.6	138.4	658.9
	Lower Block Coal (lower bench 44–66 cm)	856.4	147.2	1,003.6
	Lower Block Coal (full channel 0–66 cm)	538.3	132.8	671.1
VARIOUS MINES GRAB SAMPLES	Danville Coal (Bear Run Mine grab)	214.2	59.1	273.3
	Washed Danville (Bear Run Mine grab)	309.8	76.6	386.5
	Hymera Coal (Bear Run Mine grab)	196.2	54.1	250.3
	Bucktown Coal (Bear Run Mine grab)	184	82.7	266.8
	Springfield Coal (Bear Run Mine grab)	349.4	110.6	460
	Three coals blend (Bear Run Mine grab)	387.3	82.3	469.6
	Springfield Coal 1 (Oaktown Mine grab)	240.4	73.3	313.6
	Washed Springfield 1 (Oaktown Mine grab)	206.1	72.3	278.3
	Springfield Coal 2 (Oaktown Mine grab)	121.2	42.7	163.9
	Washed Springfield 2 (Oaktown Mine grab)	438.6	130	568.5
	Washed Springfield (Francisco Mine grab)	381.5	94.3	475.8

Table 6. Concentrations of selected critical elements in Indiana coals. Compiled from Mastalerz and others (2009).

Element	Average (ppm)	Minimum (ppm)	Maximum (ppm)	Number of analyses	World average (ppm)	U.S. average (ppm)
Arsenic	16.51	0.4	156	289	7.6–9	6.5
Cobalt	8.9	1	31.2	286	4.2–6	7.1
Chromium	14.31	0.07	75	288	2.2–28	22
Gallium	4.58	1.4	12.3	218	5.5–6	5.7
Germanium	14.74	1.44	48.84	220	2–2.4	5.7
Lithium	10.69	0.67	63.04	220	10–14	16
Nickel	32.08	4.4	116	300	9–17	14
Manganese	38.96	2.25	313.3	240	<100	43
Uranium	2.02	0.27	17	219	1.9–2.9	2.1
Vanadium	25.9	3.3	209.67	274	22–28	22

REEs in Indiana coals are dominantly associated with mineral matter (Mastalerz and others, 2020), the mineral-rich waste of these coals could be viable sources of REEs. Concentrations of REEs in the most economically important coals, such as the Springfield Coal Member of the Petersburg Formation and the Danville Coal Member of the Dugger Formation, are lower and fall below the 800 to 900 ppm threshold (Tables 4 and 5) but these coal beds are thicker, thus compensating to some extent for their lower REEs concentrations.

2.1.3 Other critical elements in Indiana coals

A summary of the concentrations of numerous elements in individual coal beds in Indiana is provided in Mastalerz and others (2009), and Table 6 gives an overview of selected elements for all coals in comparison to world and U.S. coal averages. In general, the concentrations in Indiana coals are within the range documented from other U.S. and world coals, except Germanium (Ge) which shows significant enrichment both in comparison to the world and U.S. coals.

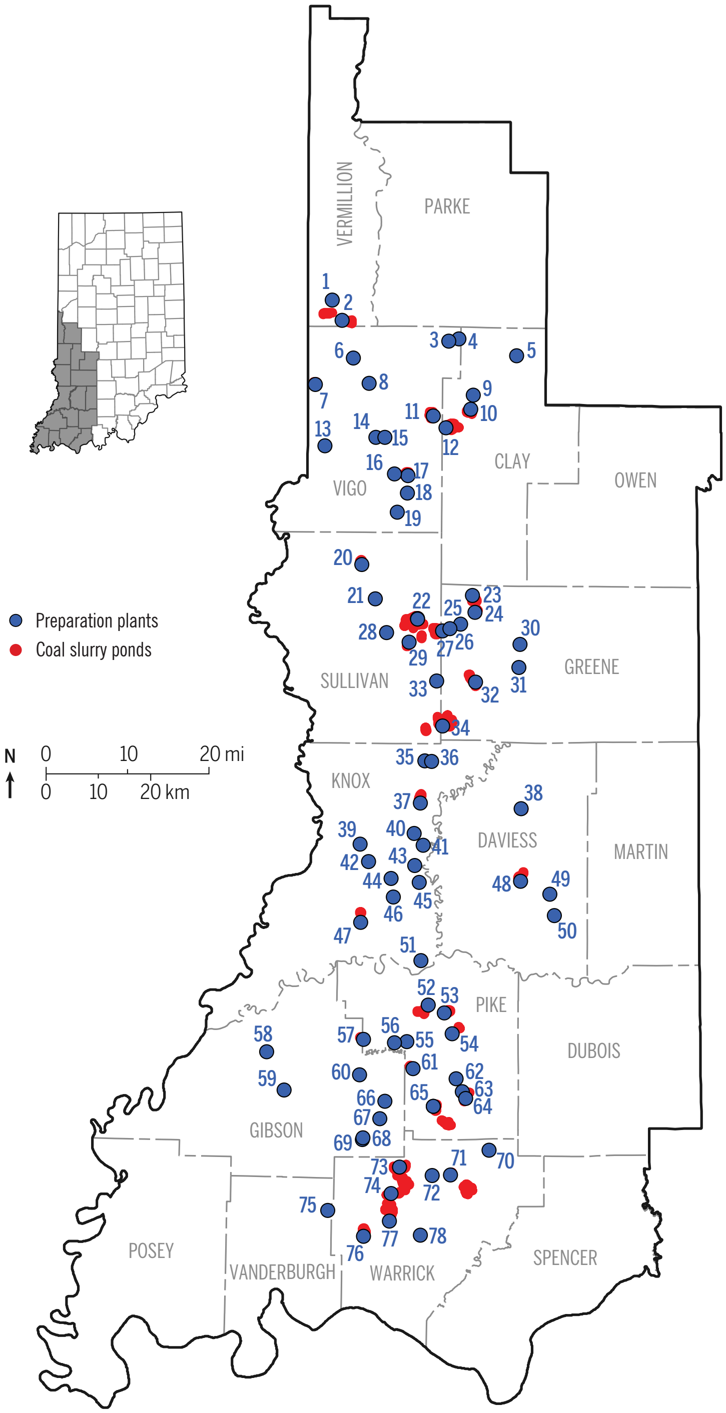
Four critical elements, arsenic (As), zinc (Zn), gallium (Ga), and germanium (Ge), were the subject of detailed studies in two main coal beds of economic interest in Indiana: the Springfield Coal Member of the Petersburg Formation and the Danville Coal Member of the Dugger Formation (Mastalerz and Drobniak, 2012, 2007).

Arsenic (As) content in the Danville and Springfield coals shows similar ranges from 0.5 to 43 ppm (whole-coal basis) for the Danville Coal and 1 to 50 ppm for the Springfield Coal, with an average of 12.7 ppm for the Danville and 9.4 ppm for the Springfield. Based on relationships of As with ash and sulfur content, and the change of its concentration during coal washing, Mastalerz and Drobniak (2007) suggested that As had multiple origins in Indiana coals; it could be associated with the late-fracture-filling pyrite variety (epigenetic origin), early-stage, very-fine-grained pyrite (syngenetic origin), or less commonly with organic matter. The coal in which As is associated with fracture-filling pyrite would be the best source of As; it would get easily concentrated in high-density reject material during coal washing. On average, in Indiana coals, As is reduced by 37% (thus concentrated in coal reject) by washing (Mastalerz and others, 2009).

Zinc (Zn) content for the Danville Coal ranges from 9.2 to 331 ppm, with an average of 109.3 ppm, and for the Springfield Coal the range is 6.5 to 494 ppm, averaging 59.89 ppm (Mastalerz and others, 2009). In these coals, Zn does not correlate with pyritic sulfur content nor ash yield, but it gets dramatically reduced in the float fraction as a result of washing, suggesting that it is hosted by a high specific gravity mineral, likely sphalerite (ZnS), filling cleats and fractures in coal (Mastalerz and Drobniak, 2007). In Indiana coals, on average, Zn is reduced by 46% in coal (thus concentrated in coal reject material) as a result of washing (Mastalerz and others, 2009).

Gallium (Ga) in the Danville and the Springfield Coals shows similar ranges, with 1.7 to 8.9 ppm (average 5.06 ppm) for the Danville and 1.4 to 12.30 ppm (average 3.39 ppm) for the Springfield (Mastalerz and Drobniak, 2012). Gallium content in coal is lower than that of the associated clastic sediments, suggesting its association with minerals rather than the organic fraction.

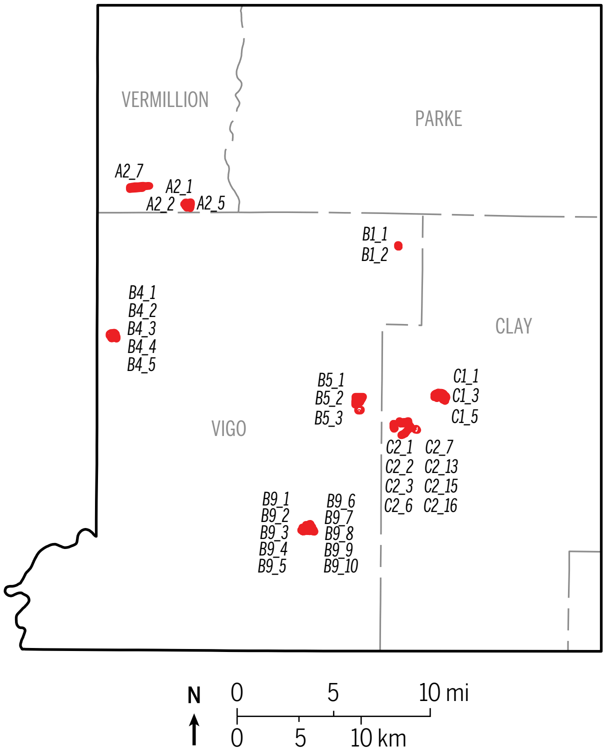
Germanium (Ge) content ranges from 2.5 to 26.7 ppm (average 14.19 mm) for the Danville and 1.54 to 38.0 ppm (averaging 9.4 ppm) for the Springfield (Mastalerz and Drobniak, 2012). In contrast to Ga, Ge shows increased concentrations in coal compared to associated clastic sediments. Mastalerz and Drobniak (2012) suggested that organic matter in the coal was an effective scavenger of Ge from the circulating fluids. With increased concentrations of Ge coals in comparison to other coals (Table 6), Indiana coals could be a good source of Ge.



1–Sunspot
2–Universal
3–Otter Creek
4–unknown
5–Rio Grande
6–Talleydale
7–Green Valley-Wabash
8–Saxton No. 1
9–Lone Star
10–Old Chinook
11–Victory
12–Chinook
13–Dresser
14–Springhill
15–Mt. Pleasant
16–Chieftain No. 20
17–Chieftain No. 20
18–Black Hawk
19–Farmersburg
20–Thunderbird
21–Jonay
22–Little Betty
23–Latta
24–unknown
25–Ax
26–Fourth Vein
27–New Hope-Friar Tuck
28–Pandora
29–Regent
30–Miller Creek
31–Switz City
32–Airline
33–Allendale
34–Hawthorn
35–Freelandville No. 1
36–Freelandville No. 2
37–Shasta
38–Maid Marian
39–Enoco

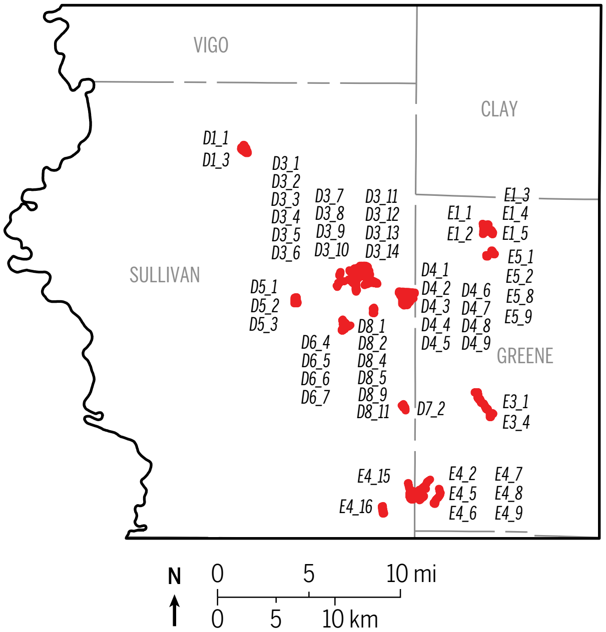
40–American No. 2
41–Sycamore
42–Julian
43–Apraw
44–White Ash
45–Standard No. 2
46–Air Quality
47–Monroe City
48–Viking
49–Cannelburg
50–Corning
51–Pride
52–Prides Creek
53–Old Ben No. 2
54–Black Foot No. 5
55–Wick
56–Oatsville
57–Patoka River
58–Gibson County
59–Kings Station
60–Francisco
61–Columbia
62–Augusta
63–Black Foot No. 2
64–Black Foot No. 2
65–Old Ben No. 1
66–Somerville North
67–Somerville Central
68–Enterprise
69–Buckskin
70–Deer Ridge
71–Tecumseh Nos. 3-4
72–Buckskin-Tecumseh No. 2
73–Lynville
74–Lynville South
75–Vanderrick
76–Ayrshire
77–Squaw Creek
78–Sunlight

Figure 9. Location of coal preparation plants and coal slurry ponds in Indiana after Harper and others (2009) and Mastalerz and others (2022b). See figures 10–13 for more detailed locations, area, and volume of the ponds.



ID-IGS-PLY	Area [acres]	Volume [m^3]
A2_1	16.6	205,105
A2_2	10.8	132,855
A2_5	23.7	292,334
A2_7	69.3	6,407,198
B1_1	2.7	16,403
B1_2	0.4	2,239
B4_1	3.2	78,758
B4_2	9.8	121,151
B4_3	4.9	120,111
B4_4	10.6	261,819
B4_5	6.3	156,015
B5_1	4.4	272,132
B5_2	80.5	496,784
B5_3	6.9	42,702
B9_1	15.7	582,211
B9_2	2.5	91,363
B9_3	2.8	23,959
B9_4	42.2	364,227
B9_5	4.7	40,320
B9_6	4.8	41,369
B9_7	1.7	21,478
B9_8	1.7	21,234
B9_9	0.3	11,293
B9_10	0.9	33,317
C1_1	36.4	1,257,460
C1_2	11	813,994
C1_3	35.6	1,754,269
C1_5	21.1	1,041,386
C2_1	6.4	631,532
C2_2	0.7	65,218
C2_3	3.5	300,952
C2_6	5.6	381,494
C2_7	15.9	1,079,261
C2_13	9	939,085
C2_15	10.1	1,558,519
C2_16	2	208,507

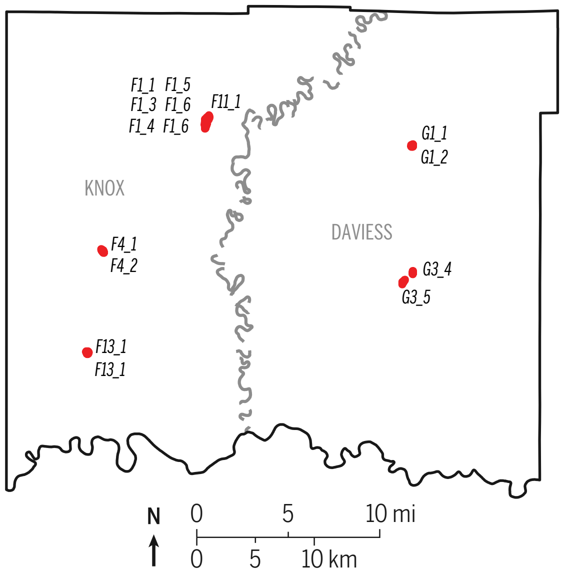
Figure 10. Coal slurry pond locations, area, and volume in Vermillion, Vigo, and Clay Counties. Note that the size of the ponds on the map is not to scale. From Mastalerz and others (2022b).



ID-IGS-PLY	Area [acres]	Volume [m³]
D1_1	53.8	994,999
D1_3	15.1	280,208
D3_1	43.3	1,068,815
D3_2	6.8	83,555
D3_3	2.3	86,816
D3_4	2.8	24,019
D3_5	9.2	79,363
D3_6	9	77,314
D3_7	4.7	175,091
D3_8	5.8	213,960
D3_9	16.3	241,545
D3_10	7.8	106,001
D3_11	25.1	185,310
D3_12	2.5	18,310
D3_13	2	12,240
D3_14	15.6	827,315

ID-IGS-PLY	Area [acres]	Volume [m³]
D4_1	9.1	355,677
D4_2	1	8,953
D4_3	2	63,210
D4_4	0.5	14,805
D4_5	0.9	27,215
D4_6	17.3	256,574
D4_7	6.1	90,617
D4_8	38.6	524,154
D4_9	47.5	760,954
D5_1	1.7	20,619
D5_2	2.9	35,489
D5_3	32.8	405,181
D6_4	19.4	479,728
D6_5	14.4	177,016
D6_7	4.5	27,687
D7_2	22.2	547,431
D8_1	12	1,179,700
D8_2	3.2	275,928
D8_4	6.6	81,964
D8_5	15.6	1,349,282
D8_9	10.4	1,537,590
D8_11	23.7	1,313,303
E1_1	32.6	321,952
E1_2	17.8	175,639
E1_3	35.5	350,203
E1_4	10.7	105,861
E1_5	15	148,115
E3_1	47.8	3,241,587
E3_4	18.7	175,639
E4_2	55.3	2,184,282
E4_5	15.7	965,317
E4_7	2.8	172,358
E4_8	2.7	201,998
E4_9	20.2	1,991,769
E4_15	28.1	2,255,909
E4_16	20.4	2,641,711
E5_1	2.4	29,921
E5_2	3.9	33,504
E5_8	4	34,318
E5_9	11.4	98,621

Figure 11. Coal slurry pond locations, area, and volume in Sullivan and Greene Counties. Note that the size of the ponds on the map is not to scale. From Mastalerz and others (2022b).



ID-IGS-PLY	Area [acres]	Volume [m^3]
F1_1	0.8	63,702
F1_3	4.1	50,754
F1_4	2.0	24,787
F1_5	6.6	81,826
F1_6	11.7	144,854
F1_7	2.9	231,777
F4_1	13.1	404,154
F4_2	1.5	9,419
F9_1	2.1	91,066
F9_3	4.4	270,297
F11_1	35.3	261,009
F13_1	4.3	26,756
F13_2	13.8	255,666
G1_1	7.3	447,649
G1_2	1.2	73,600
G3_4	7.6	560,600
G3_5	12.4	613,379

Figure 12. Coal slurry pond locations, area, and volume in Knox and Daviess Counties. Note that the size of the ponds on the map is not to scale. From Mastalerz and others (2022b).

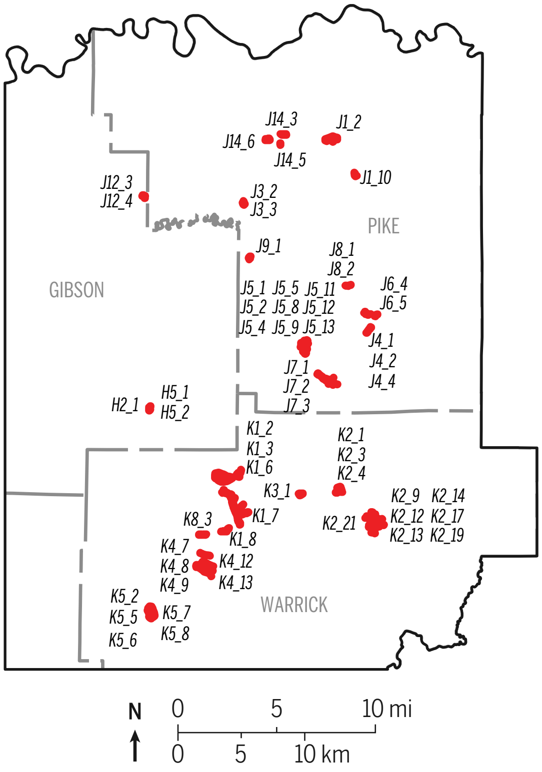
2.2 Coal preparation plant refuse as a source of REE-CM

Indiana has a long history of coal mining (~150 years, fig. 6) and is still a major coal producer (~24,000,000 short tons in 2024). Due to the high sulfur contents of most Indiana coals (e.g., Mastalerz and others, 2009), the vast majority of the coal has been washed in coal preparation facilities to meet coal quality specifications. Consequently, in addition to the clean coal product, these preparation plants generate coal waste—rejects from the coal cleaning process. Rejects can be broadly classified as coarse-grained refuse (also called "gob") and fine-grained refuse (also known as coal tailings or slurry). This coal waste material is typically deposited near coal preparation facilities. After passage of the Surface Mining Control and Reclamation Act (SMCRA) in 1977, coal mine operators were required to reclaim their coal waste after mining terminated, and the Abandoned Mine Lands (AML) program was instituted (Harper and others, 2009). Most of the waste sites have since been revegetated after being covered by a cap of soil, synthetic soil, or spoil, or after the application of large quantities of agricultural limestone. Coal preparation plant waste in Indiana is discussed below in chapters 2.2.1 (finer-grained refuse; tailings, slurry ponds), 2.2.2 (acid mine drainage, AMD, sites) and 2.2.3 (coarse grained refuse; gobs). Chapter 2.2.4 discusses spoil ridges, also a potential source of REE-CM.

2.2.1 Fine-grained refuse (coal tailings, coal slurry deposits)

Indiana has numerous coal preparation plants and associated coarse- and fine-grained coal refuse (fig. 9), and starting in the early 1970s, several studies attempted to map Indiana's coal waste deposits (Mastalerz and others, 2022b). In 2009, Harper and others (2009) conducted a comprehensive study of coal slurry deposits. In that study, maps, reports, and historical aerial photographs were georeferenced, slurry deposits were identified, and their extent and volumes were estimated. Shapefiles with accompanying preparation plant information are available from the Indiana Geological and Water Survey. Locations, areas (in acres) and volumes (in cubic meters, m^3) for individual slurry deposits are shown in figures 10–13. The total extent of the Indiana slurry pond deposits identified in Harper and others (2009) was estimated at 2,765 acres, and the total volume estimate ranged from 94,000,000 to 136,000,000 cubic yards (71,868,156 to 103,979,460 m^3). In consideration of mining feasibility, they further estimated that potentially mineable raw slurry in Indiana would range from 74,000,000 to 171,000,000 tons.

Slurry deposits contain fine-grained refuse and, as such, are composed of small coal fragments mixed with mineral matter, dominantly clay minerals. The average ash and sulfur contents (as-received basis) of 454 slurry samples from Indiana are 31.4 %, and 4.1 %, respectively (Table 7).



ID-IGS-PLY	Area [acres]	Volume [m^3]
H2_1	4.5	55,285
H5_1	2.1	25,547
H5_2	1.4	8,332
J1_10	9.9	791,154
J12_3	5.6	479,466
J12_4	3.1	271,035
J14_3	12.2	1,882,926
J14_5	2.2	332,036
J14_6	15.9	1,857,794
J3_2	0.3	4,186
J3_3	10.2	125,463
J4_1	5.8	107,670
J4_2	1.6	29,292
J4_4	2.7	33,802
J5_2	20.2	124,313
J5_4	3.6	199,330
J5_5	0.4	22,394
J5_8	1	53,820
J5_9	5.2	287,326
H2_1	4.5	55,286
H5_1	2.1	25,547

ID-IGS-PLY	Area [acres]	Volume [m^3]
J5_1	12.2	120,858
J5_11	1.1	52,169
J5_12	33.1	327,019
J5_13	1.4	13,500
J6_4	11.8	145,233
J6_5	4.7	40,909
J7_1	11.4	98,702
J7_2	3.7	32,068
J7_3	37.5	324,118
J8_1	2.7	133,866
J8_2	1.1	47,897
J9_1	7.7	190,527
K1_2	117.6	4,350,487
K1_3	85.2	3,677,096
K1_6	26.1	1,222,514
K1_7	99.9	12,932,762
K1_8	25.9	2,880,578
K2_1	3.8	93,626
K2_3	31.7	2,108,742
K2_4	3.2	77,759
K2_9	11	204,005
K2_12	16.8	727,009
K2_13	3.9	166,260
K2_14	5.3	227,664
K2_17	3.3	101,846
K2_19	0.6	17,619
K2_21	1.7	30,549
K3_1	14	277,273
K4_7	8.9	749,097
K4_8	9.9	828,761
K4_9	10.5	881,364
K4_12	3.8	322,011
K4_13	13.4	1,122,466
K5_2	33.9	1,255,800
K5_3	16.9	625,248
K5_5	4	197,048
K5_6	9.1	558,710
K5_7	8.9	441,338
K5_8	50.3	3,101,959
K8_1	12.9	1,756,885
K8_3	11.4	1,547,857

Figure 13. Coal slurry pond locations, area, and volume in Gibson, Pike, and Warrick Counties. Note that the size of the ponds on the map is not to scale. From Mastalerz and others (2022b).

Table 7. Ash yield, sulfur content, and heating value of slurry deposits in Indiana. ar – as received; maf – moisture ash-free basis (from Harper and others, 2009).

Mine	IGS ID	No. drill holes	No. samples	Ash (ar, wt. %)	Sulfur (ar, wt. %)	Btu/lb (ar)	Btu/lb (maf)
Airline	E3	11	99	42.4	4.4	7,143	12,657
Buckskin	K3	7	17	29	2.7	8,589	12,873
Chinook	C1	14	81	30.5	3.2	5,577	13,310
Friar Tuck	D4	9	37	28.1	2.1	8,092	13,663
Green Valley	B4	9	23	20.9	5.1	9,780	13,305
Hawthorn	E4	11	55	45.2	5.8	6,608	11,920
Lynnville	K1	6	36	35	4.3	8,150	13,344
Minnehaha	D3	18	74	20.2	2.2	6,893	13,680
Otter Creek	B1	4	4	26.7	2.6	8,893	13,025
Tecumseh	K2	4	28	35.9	8.9	7,168	11,942
Sum		93	454				
Average				31.4	4.1	7,689	12,972

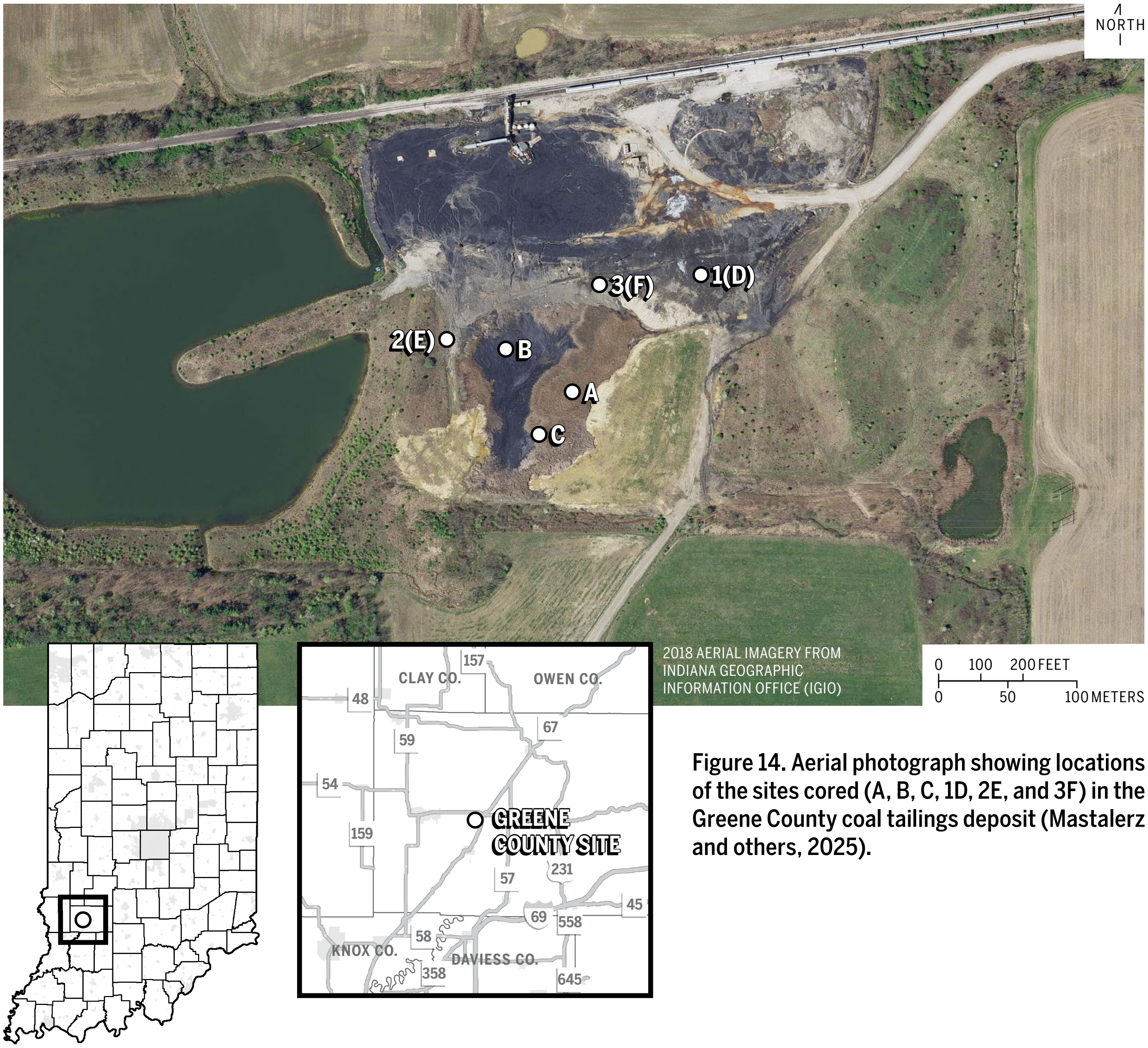


Figure 14. Aerial photograph showing locations of the sites cored (A, B, C, 1D, 2E, and 3F) in the Greene County coal tailings deposit (Mastalerz and others, 2025).

Figure 15. Aerial photograph showing locations of the sites cored (A, B, C, 1A, and 2) in the Pike County coal tailings deposit (Mastalerz and others, 2025).

Heating values (as-received basis) average 7,689 Btu/lb, and on moisture ash-free basis, 12,972 Btu/lb, testifying to large proportions of coaly material remaining in the slurry deposits.

Numerous new data on critical minerals in Indiana coal waste have been added as part of a DOE-supported CORE-CM project (Mastalerz and others, 2025). In that study, samples of coal tailings were obtained from two sites: one in Greene County (fig. 14) and the other one in Pike County (fig. 15), Ind. These two sites provided data on coal waste from different coal types: a) the high-sulfur Springfield Coal (processed in a Pike County preparation plant—it was a heavily mined area during 1921–1945, 1959–1976, and 1976–1982) and b) the relatively lower-sulfur Tradewater Formation coals (processed in a Greene County facility during 1991–2002). Several sites were drilled and core samples were collected in both locations, providing data covering the entire thickness of the waste deposits. Table 8 compares average concentrations of selected elements between these two deposits, whereas Tables 9 and 10 list REE concentrations of the samples from the locations cored.

Table 8. Comparison of the averages of selected parameters between the two coal tailing deposits.

Elements	Greene County	Pike County
C (%, dry)	52	73.3
S (%, dry)	2.7	5.6
Ash (%, dry)	35	33.8
Al (%)	8.3	9.9
As (ppm)	89.5	51.7
Co (ppm)	60.9	19.9
Ga (ppm)	32.9	29.6
Ge (ppm)	50.2	35.7
V (ppm)	182.5	198.8
Zn (ppm)	450.9	260.6
REE+Y+Sc (ppm, ash basis)	475.4	413.3
REE+Y+Sc (ppm, whole-rock basis)	164.7	130.8
Vitrinite (vol %, mineral-matter-free)	47.7	73.7
Liptinite (vol %, mineral-matter-free)	5.3	5.4
Inertinite (vol %, mineral-matter-free)	47.7	20.9

Table 9. Rare earth element data (ppm, on ash basis) from the Greene County deposit. * values in UCC (upper continental crust). Locations A, B, C, 1D, 2E, and 3F correspond to those in fig. 14.

ID	Sample	Depth (ft)	Total REE (ash basis)	Total REE + Y+Sc (ash basis)	Light REE (ash basis)	Heavy REE (ash basis)	Y (ash basis) (21)*	Sc (ash basis) (14)*	Ash (dry basis)
106	A1	0–4	234.9	267.8	220.8	14.2	22.9	9.9	94.8
107	A2	4–8	342.9	398.4	321.7	21.2	35.6	19.9	46
108	A3	8–12	359.1	413	337.2	21.8	35.9	18	28
109	A4	12–14	415.9	483.8	389.5	26.3	43.5	24.4	20.9
110	A5	14–16	377.5	434.8	354.9	22.5	37.6	19.7	24
111	A6	16–18	452	527.6	425	27	46.1	29.6	17.1
112	A7	18–20	384.3	439.4	363.3	21	35.6	19.5	31.4
113	B2	4–8	414.9	474.9	392.4	22.5	37.5	22.5	64.4
114	B3	8–12	403.1	471	377.6	25.5	43.4	24.5	20.5
115	B4	12–14	359.9	417.2	337.8	22.2	37.7	19.6	28
116	B5	14–16	429.6	490.3	406	23.6	39.6	21.1	33.9
117	B6	16–18	437	503	412.2	24.8	42.1	23.9	37.3
118	B7	18–20	525.9	604.4	495.5	30.4	52.3	26.2	31.41
119	C2	7–8	237.3	273.4	222	15.3	26.1	9.9	50
120	C3	8–12	435.1	498.2	410.6	24.5	40.3	22.7	40.4
121	C4	12–14	461.1	542.9	429.7	31.4	53.1	28.7	16.4
122	C5	14–16	475.3	539.4	450	25.4	41.2	22.9	43.6
123	C6	16–18	440.8	503.3	416.6	24.1	39.1	23.4	44.9
124	C7	18-20	473.1	541.9	446.4	26.7	44.2	24.7	51
170	1(D)1	0–1.5	279.04	329.4	262.1	16.9	37.2	13.1	93.8
171	1(D)2	1.5–2.7	345.83	399	329.6	16.1	33.4	19.8	61.5
172	1(D)3	2.7–4.0	315.02	384.3	295.7	19.2	45	24.2	58.8
173	1(D)4	4.0–6.0	287.53	341.7	271.8	15.7	31.9	22.3	84.7
174	1(D)5	6.0–8.0	354.04	421.6	333.1	20.8	42.3	25.3	92
175	2(E)1	0–2	237.65	279.6	223.6	14	27.3	14.6	95.7
176	2(E)2	2–4	504.2	585.2	482.7	21.4	42.7	38.2	71.5
177	2(E)3	4–6	498.31	574.2	475.6	22.6	43.2	32.7	78.5
178	2(E)4	6–8	381.17	460.5	357.4	23.7	47.9	31.4	88.8
179	2(E)5	8–10	376.49	447.9	353.8	22.6	44.8	26.6	90.4
180	2(E)6	10–12	394.73	465.9	371.2	23.5	46.8	24.3	91.3
181	3(F)1	0–2	246.81	286.5	232.3	14.4	28.1	11.6	92.7
182	3(F)2	2–4	284.13	338.4	266.6	17.4	34.4	19.8	84.8
183	3(F)3	4–6	331.12	395.3	311	20.1	39.7	24.5	88

The main findings from the study of the two coal tailing deposits are as follows:

a.) Coal tailings have variable but high carbon content, often exceeding 50 %. Correspondingly, ash content is variable, decreasing with an increase in C content. Sulfur content is generally higher in the Springfield Coal tailings than in the Tradewater Formation coals, a reflection of high S content in the original Springfield Coal.

b.) Quartz and clay minerals are prominent inorganic components in both deposits, with more aluminum-rich clays present in the Greene County deposit. Kaolinite and illite are the dominant clay minerals in both.

Table 10. Rare earth element data (ppm, on ash basis) from the Pike County deposit. * values in UCC (upper continental crust). Locations A, B, C, 1A, and 2 correspond to those in fig. 15.

ID	Sample	Depth (ft)	Total REE, (ash basis)	Total REE +Y+Sc (ash basis)	Light REE (ash basis)	Heavy REE (ash basis)	Y (ash basis) (21)*	Sc (ash basis) (14)*	Ash (dry basis)
125	A1	0–2	157.7	183	148.6	9.1	17.1	8.2	51.3
126	A2	2–4	167.4	193.8	157.5	9.9	18.5	7.9	40.9
127	A3	4–6	202.3	233.2	190.4	11.9	22	8.9	36.3
128	A4	6–8	236.6	275.7	222.6	14	26.2	12.9	30.1
129	A5	8–10	325.5	366.2	311.6	13.9	24.3	16.4	60
130	A6	10–12	295	348.5	278	17	31.6	21.9	26
131	A7	12–14	211.9	242.5	200.7	11.2	20.7	9.9	34.6
131	A8	14–16	187.1	209.9	179.3	7.8	14.1	8.7	38.8
133	B1	0–2	145.1	167.3	136.6	8.5	16.2	6	38.8
134	B2	2–4	184.3	209.4	174.8	9.5	18.5	6.6	39.9
135	B3	4–6	236.1	270.2	223.7	12.4	24.8	9.3	39.2
136	B4	6–8	230.8	263.5	222	8.8	18	14.7	41.7
137	B5	8–9.5	259.8	313.9	242.9	16.9	39.6	14.5	48.3
138	C1	0–2	206.4	238.5	195.1	11.3	21.8	10.3	37.7
139	C2	2–4	203.3	238.2	191.4	11.9	23.6	11.3	32.6
140	C3	4–6	305.6	348.9	292	13.6	26.1	17.2	44.8
141	C4	6–8	296.2	354.1	278.6	17.6	35.8	22.1	22.7
142	C5	8–9.5	284.3	332	268.5	15.8	31.5	16.2	25.6
146	1A1	0–2	321.8	379.1	304.5	17.3	34.9	22.3	66.5
147	1A2	2–4	259.3	309	245.5	13.8	30.5	19.1	38.4
148	1A3	4–6	265.3	317.7	250.8	14.4	33.3	19	31.1
149	1A4	6–8	401.2	483.6	377.3	23.9	52.8	29.5	20.9
150	1A5	8–10	324.2	388.7	305	19.1	42.4	22	24.8
151	1A6	10–12	350.6	425	329.3	21.3	45.3	29.1	21.6
152	1A7	12–14	415.2	524.7	381.5	33.6	73.3	36.1	12.2
153	1A8	14–16	433.7	522	406.2	27.5	61	27.2	13.2
154	1A9	16–18	372.1	430.7	354.1	18	39.2	19.3	15.4
155	2_1	0–2	405.6	468.4	387.9	17.7	35.6	27.1	37.8
156	2_2	2–4	484	565.4	458.2	25.7	48	33.4	44.2
157	2_3	4–6	520.8	600.3	494.8	26	49.6	29.8	39.8
158	2_4	6–8	548.2	654.8	514.5	33.6	75.6	30.8	34.9
159	2_5	8–10	612.3	711.4	582.1	30.2	65.8	33.1	35.2
160	2_6	10–12	532.2	615.2	506.2	25.9	53.3	29.5	37.8
161	2_7	12–14	528.7	602.3	506.7	22	43.4	30.1	38.2
162	2_8	14–16	615.7	701.8	586	29.6	56.7	29.3	34.7
163	2_9	16–18	556.7	641.2	530.5	26.2	55.8	28.6	25.3
164	2_10	18–20	487.1	581.5	457.2	29.9	64.6	29.7	16.4
165	2_11	20–22	450.6	551.9	418.4	32.1	70.6	30.7	14.4
166	2_12	22–24	478.6	590.4	442.6	35.9	77.7	34	12.5
167	2_13	24–26	512.5	631.4	473.9	38.5	83	35.9	12.4
168	2_14	26–28	449.8	548	419	30.7	66.8	31.3	17.7
169	2_15	28–32	269.5	323.5	253.4	16.1	34	19.9	82.9

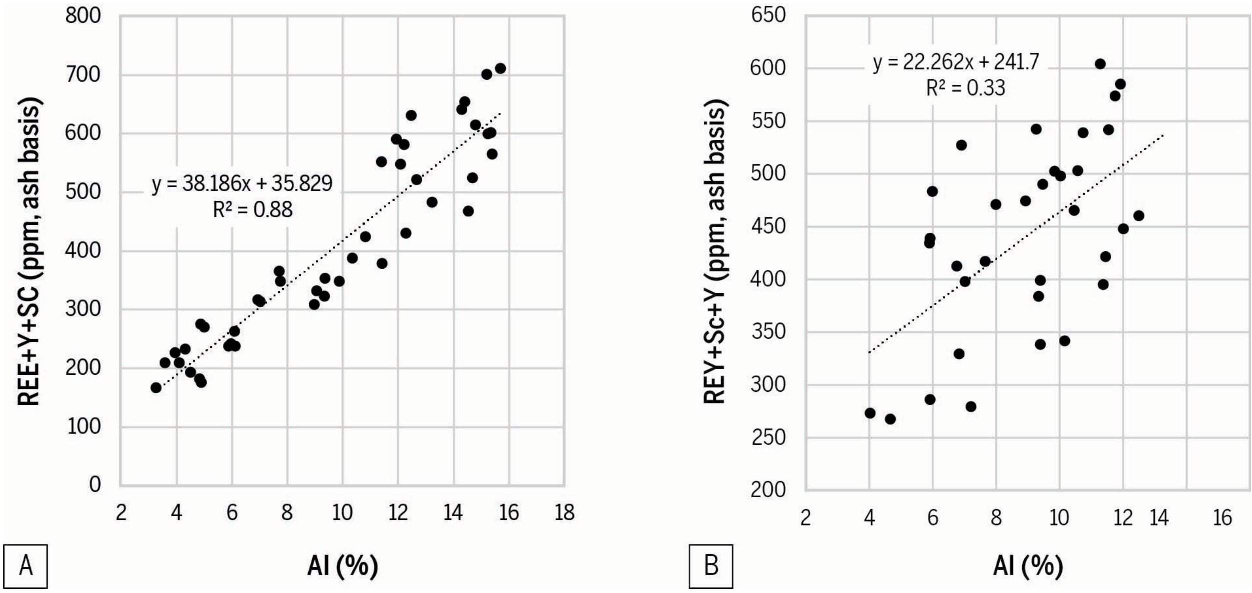


Figure 16. Scatter plots and regressions showing a relationship between aluminum (Al) and REEs and the Pike County (A) and Greene County (B) deposits (Mastalerz and others, 2025).

c.) There are systematic differences in maceral composition between the two deposits: more inertinite and less vitrinite in the Tradewater Formation tailings, also a reflection of higher vitrinite content in the original Springfield Coal.

d.) Coal tailings in Greene County have higher concentrations of critical elements such as As, Co, Ga, Ge, and Zn than those in Pike County.

e.) There are more REEs in the Greene County coal tailings than in the Pike County coal tailings. On ash basis, the range is 267 to 604 ppm in Greene County (475.4 ppm on average) compared to

Table 12. Example of potential yields of total REE concentrations with differing flow rates (in gallons per minute) in AMD. Potential yields shown for hourly (mg/hr), daily (g/day), quarterly (g/gtr, lbs/qtr), and annual (lbs/yr) collection.

Total REEs mg/L	Est. flow rate gal/min	Yields of total REEs					
		mg/gal	mg/hr	g/day	g/qtr	lbs/qtr	lbs/yr
4	1	15.1	908	22	1,990	4	18
4	2	15.1	1817	44	3,979	9	35
2	2	7.6	908	22	1,990	4	18
2	5	7.6	2,271	55	4,974	11	44
1	5	3.8	1,136	27	2,487	5	22
1	10	3.8	2,271	55	4,974	11	44
0.5	20	1.9	2,271	55	4,974	11	44
0.5	40	1.9	4,542	109	9,948	22	88

Table 11. Potential indicators or proxy elements for locating total REE concentrations of >1,000 μg/L in AMD.

Indicator	Indicator threshold	Sites with REE >1,000 μg/L	Sites with REE <1,000 μg/L
Aluminum	100 mg/L	94 %	22 %
Nickel	0.6 mg/L	83 %	38 %
Magnesium	200 mg/L	72 %	31 %
Cobalt	0.25 mg/L	61 %	38 %
Nickel	1.0 mg/L	56 %	31 %
Factor 1 loading	0.2	56 %	6 %
Factor 1 loading	0.4	56 %	0 %

Table 13. Example of quantities of solid waste material required to be excavated to generate an equivalent amount of REEs obtained quarterly from AMD streams of various concentrations and flow rates.

REE concentration	Amount of REEs per mass unit		Amount of solid waste to be excavated	
mg/kg	g/lb	lb/short ton	Short tons/9 lbs REEs	Short tons/11 lbs REEs
500	1.1	4.9	1.6	2.2
250	0.55	2.4	3.3	4.6

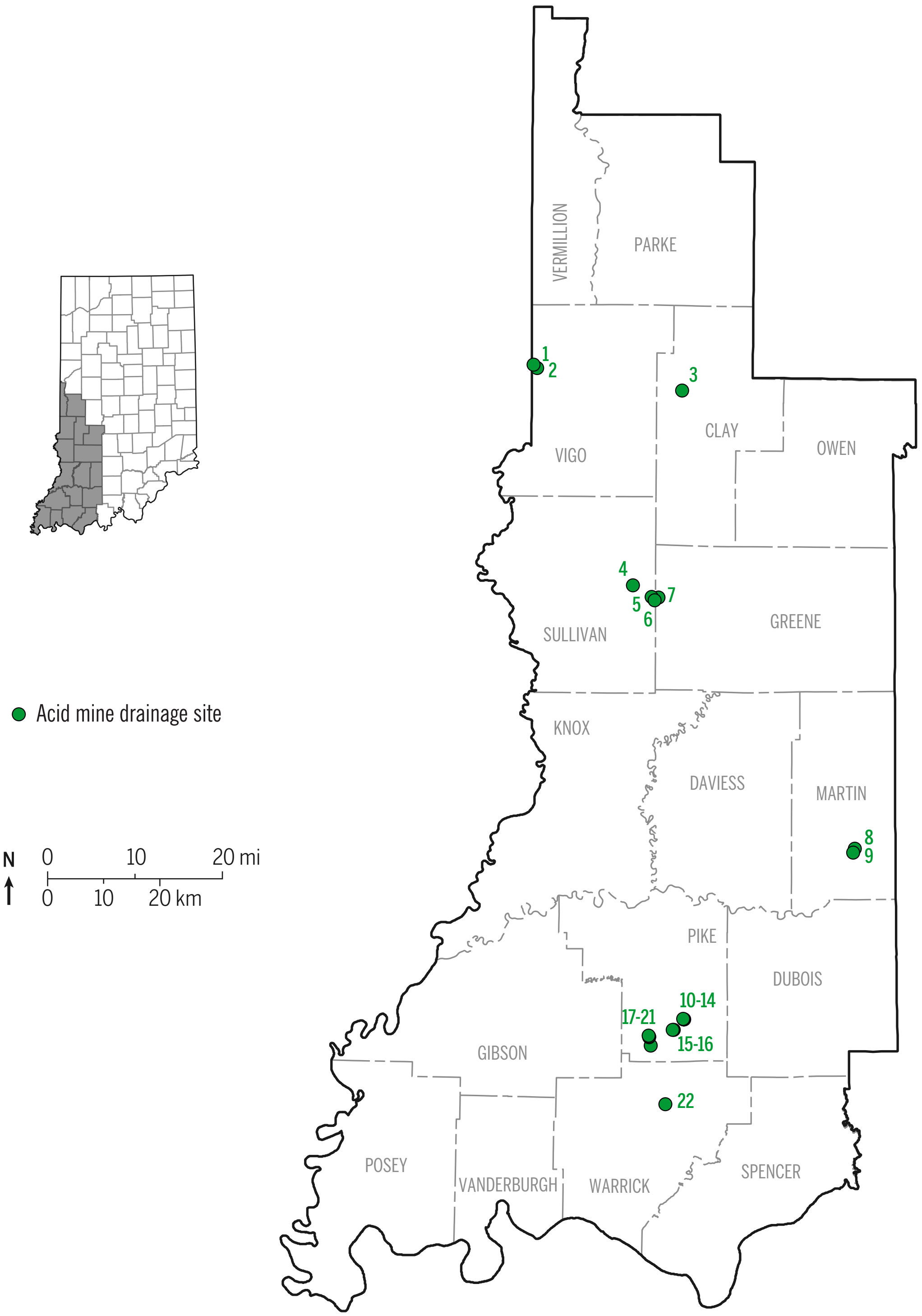


Figure 17. Map showing known acid mine drainage sites in Indiana (Mastalerz and others, 2022b). 1–Green Valley B; 2–Green Valley A; 3–Chinook N Seep; 4–Minnehaha Gob; 5–Friar Tuck STR4 and STR5; 6–Friar Tuck STR2; 7–Friar Tuck Seep 108; 8–Lacy Bioreactor Outlet; 9–Lacy Seep 2; 10–Midwest Seep SP2A; 11–Midwestern Bioreactor; 12–Midwestern Seep; 13–Midwestern Oxidation Pond; 14–Midwestern Seep SW9A; 15–Blackfoot MOAS Seep; 16–Blackfoot SRB Seep; 17–Enos Outlet; 18–Enos Bioreactor; 19–Enos VFP Outlet; 20–Enos Acidic Pond; 21–Enos Seep; 22–Tecumseh Seep.

Table 14. REE concentrations (in micrograms per liter) from AMD seeps in Indiana.

	ELEMENTS (all values in µg/l)														
Sites sampled	**Y**	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
Green Valley A	749.5	58.96	201.3	42.62	200.5	115.7	34.78	138.3	30.71	149.1	31.13	73.91	9.94	52.27	8.4
Green Valley B	674.9	102.4	371.1	61.76	220.1	99.47	30.47	131.3	28.18	137.7	28.51	69.26	9.15	48.1	7.7
Friar Tuck Seep 108	1,791	120.4	690.4	138.6	650.6	242.9	72.06	278.7	53.46	244.8	57.59	143.9	17.9	105.1	17.13
Lacy Seep	152.7	9.978	77.09	17.79	86.87	30.4	7.981	30.61	5.396	24.64	5.182	11.49	1.428	6.827	1.05
Lacy Bioreactor Outlet	1.002	0.272	0.74	0.065	0.245	0.077	0.044	0.091	0.013	0.065	0.016	0.035	0.005	0.02	0.004
Midwest Seep	119.2	19.39	82.55	14.18	52.62	17.53	5.137	21.17	4.099	16.15	3.984	8.59	1.112	5.194	0.843
Midwest Bioreactor Outlet	11.17	3.662	8.121	1.081	3.939	0.953	0.25	1.434	0.206	0.896	0.203	0.431	0.047	0.196	0.032
Blackfoot Seep	839.7	54.36	360.8	81.32	393.9	142.1	35.84	158.8	27.93	131	26.55	62.42	8.739	41.46	7.002
Enos Seep	27.17	20.11	44.55	7.204	19.76	5.882	1.338	6.318	0.926	4.164	0.907	2.039	0.27	1.292	0.211
Enos Acidic Pond	15.18	7.25	18.63	3.168	11.49	3.272	0.746	3.172	0.486	2.15	0.444	0.997	0.132	0.675	0.109
Enos Bioreactor	0.344	0.129	0.239	0.03	0.105	0.037	0.022	0.034	0.006	0.026	0.006	0.015	0.002	0.01	0.002
Enos VFP Outlet	0.279	0.261	0.836	0.05	0.178	0.053	0.022	0.059	0.008	0.034	0.008	0.02	0.003	0.015	0.003
Enos Outlet	0.111	0.126	2.128	0.026	0.083	0.035	0.026	0.042	0.005	0.017	0.004	0.01	0.002	0.009	0.002
Alcoa Seep	1,696	105.6	553.9	119.2	612.5	228.2	61.7	263.3	45.57	229.5	49.51	125.4	16.75	90.06	14.49

167 to 711 ppm in Pike County (413.3 ppm on average). This difference is more pronounced on whole-rock basis: 164.7 ppm versus 130.8 ppm on average.

f.) Aluminum content is a good predictor of REE and Ga concentrations. Positive correlations with a strong coefficient of determination clearly suggest that Al is an effective proxy for these elements and can be used to identify the most enriched parts of the deposit (fig. 16). Aluminum is quicker and cheaper to analyze for compared to REEs, so it is a good proxy for use in reconnaissance projects.

g.) Properties of coal tailings suggest that they should be further investigated for their potential utilization. Abundant coaly material (high in carbon, C) could be a potential source of higher-value carbon materials, such as activated carbon, or graphite which is a critical mineral. In turn, the inorganic fraction could be a potential source of critical elements such as Ga, Co, V, Zn, or REEs.

2.2.2 Acid mine drainage (AMD) sites

Critical minerals including REEs are found to leach from acid-generating coal waste piles and primarily from mounds of coarse material called gobs in the bituminous coal interior basins. Another source of REEs are the piles of overburden sediments known as spoil ridges (chapter 2.2.4) containing non-coal commercially non-valuable (gangue) minerals. Such sites can also leach REEs from the gangue mineral piles. A common feature in both settings is the acidic conditions generated by the oxidation of sulfide minerals, most notably pyrite and marcasite, both having the same chemical composition of FeS_2, but a different crystal structure. The acid generated through the oxidation process of these sulfide minerals is sulfuric acid (H_2SO_4) as shown in the following equation:

$$FeS_2 + 3.5O_2 + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

where H_2SO_4 is shown in the dissociated state (SO_4 and H) that occurs in aqueous solutions. The presence of acidic discharge from coal waste piles mobilizes several metals into the acidic streams, including trace metals and REEs.

Other factors also significantly influence the mobilization potential of REEs from these deposits. The primary one discovered to date is aluminum (Al). The association of REEs with Al is due to the oxidation state of the +3 characteristic of Al and all the REE elements. REEs have two oxidation states, some of the elements have a +2 oxidation state, and others have a +4 oxidation state, but all REEs have the +3 oxidation state, allowing them to form compounds similar to those formed by Al with other elements such as oxides, hydroxides, silicates,

Table 15. The number and areal extent of gob piles by county in Indiana (from Allen and others, 1978).

	100+ acres		50–100 acres		10–50 acres		< 10 acres		
County	**Number of sites**	**Acres**	**Number of sites**	**Acres**	**Number of sites**	**Acres**	**Number of sites**	**Acres**	**Total acres**
Clay					1	21	5	13	34
Davis					1	25	5	18	43
Dubois							5	5	5
Fountain							2	6	6
Gibson					4	111	2	9	120
Greene	1	122					19	53	175
Knox	1	203	4	267	3	71	4	15	556
Parke							1	2	2
Perry							4	6	6
Pike					7	151	11	35	186
Spencer							2	3	3
Sullivan			1	61	10	184	30	100	345
Vermillion					1	18	15	43	61
Vanderburgh					1	28	1	1	29
Vigo			1	84	3	38	21	48	170
Warrick					7	146	40	146	292
Total	2	325	6	412	38	793	167	503	2,033

and phosphates. This makes dissolved Al a very good indicator element or proxy for the presence of REEs in AMD, as Al is soluble in acidic solutions up to pH 4.5. Wherever elevated Al occurs in AMD, elevated concentrations of REEs should also occur. This relationship has been demonstrated with chemical data collected from AMD sites in Illinois and Indiana. A total of 50 sites were evaluated; 42 in Illinois and eight in Indiana. An arbitrary threshold of 1,000 µg/L of total REEs was used as an elevated concentration in AMD to determine the best indicator or proxy for identifying elevated REE concentrations. Table 11 shows the indicators (proxies) that were able to identify more than half of the 18 sites with elevated REEs. In addition to the elements shown in Table 11, two factor-loading scores from principal component analysis (PCA) were included. The components used in the PCA included all major dissolved parameters, AMD-associated parameters, minor and trace elements, and REEs. Because the REEs were aligned with factor 1, which accounts for the largest amount of variance in the data, loading scores for factor 1 are shown (Table 11).

Aluminum concentrations of at least 100 mg/L in AMD resulted in identifying the largest number of elevated REE sites (94 %, Table 11), with a smaller number of false positives (22 %) from the 32 sites with total REEs less than 1,000 µg/L. This demonstrates that Al is a better indicator of REE concentrations compared to other potential proxies, such as Ni or Mg.

Table 16. Indiana abandoned mine site gob pile REEs and aluminum content in AMD. Units are in ppm (parts per million) and ppb (parts per billion), which are considered equivalent to mg/L and µg/L, respectively. LREE and HREE refer to light and heavy REEs.

Gob site name	County	Al, ppm	Total REE, ppb	LREE, ppb	HREE, ppb
Alcoa	Warrick	1,005	4,113	1,631	902
Friar Tuck 108	Greene	1,055	4,461	1,834	957
Green Valley A	Vigo	596	1,758	593	473
Green Valley B	Vigo	794	1,845	826	440

Another critical factor in the economic evaluation of AMD is the combination of REE concentrations with the flow rate of AMD seeps, streams, and springs. Because REEs are already in solution, lower concentrations may still be economically viable if the flow rate is sufficiently high. Table 12 illustrates the possible yields of total REEs based on the concentration and flow rate.

The quarterly potential yields are considered the most useful, as some seasonal variations in precipitation can result in different flow rates and REE concentrations. When compared to the amount of material that would need to be excavated, transported, and processed to get REEs in solution, AMD with dissolved REEs may be the most economical way to extract REEs. For comparison, Table 13 illustrates the amount of solid excavated material required to produce equivalent yields of REEs obtained quarterly from AMD as shown in Table 12; this assumes 100 % extraction from the solid materials. Specifically, to obtain 11 lbs of REEs from solid coal waste with REE concentrations of 500 and 250 mg/kg, 2.2 and 4.6 tons, respectively, of the solid waste needs to be excavated.

For the purpose of evaluating the REE potential of AMD sites in Indiana, it is important to locate and map the extent of abandoned mine land gob piles and collect additional data points in order to evaluate the chemical composition of AMD leaching from them. Both surface and underground mine gob piles qualify for this approach to locate REE-enriched waste streams. Such piles can be found from Vigo County in western Indiana down to Warrick County on the Ohio River in southern Indiana. REE concentrations from several AMD seeps in Indiana are listed in Table 14 and the locations are shown in fig. 17. These data show wide ranges in the concentrations of all elements, but some seeps (Green Valley A, B, Blackfoot and Friar Tuck) show markedly higher values of REEs, including those elements critical with regard to supply risk (Pr, Nd, Tb, and Dy).

2.2.3 Coarse-grained refuse (gob piles)

Gob piles are coarse-grained refuse from coal preparation plants and are composed of rock fragments from coal seam partings, roof or floor clastic sediments, or coal portions rich in mineral matter. Techniques for reclaiming gob piles include diversion ditching, stream rechanneling, refuse removal, and sealing refuse with clay (Allen and others, 1978; Harper and others, 2012). A survey to determine the extent of derelict lands resulting from coal mining was conducted by the Indiana Department of Natural Resources (IDNR) in 1978 (Allen and others, 1978). The methods and detailed maps were shown in reports prepared by Purdue University Laboratory for Applications of Remote Sensing (IDNR, 1978; Weismiller and Mroczynski, 1978). The number of sites and total acres of gob piles are listed in Table 15. The extent of gob piles and slurry pond deposits was estimated at 2,033 and 1,206 acres, respectively. Harper and others (2009) conducted a comprehensive study of coal slurry deposits and reported that they span 2,765 acres. Assuming a similar gob to slurry ratio as used on the earlier study during coal mining and preparation (IDNR, 1978; Weismiller and Mroczynski, 1978), and using the updated volumes (Harper and others, 2009), the gob piles should now occupy ~4,661 acres.

Table 17. Additional gob pile AMD seeps for which aluminum data were collected. Pre- and post-recl refer to reclamation of the various sites: Friar Tuck pre-recl data is from 1988–1992, post-recl data is from 1999–2015; Midwest pre-recl data is from 1994–1995, post-recl data is from 1996–2012; Minnehaha only post-recl data is from 2012–2014.

Gob site name	County	Al ppm pre-recl	Al ppm post-recl
Friar Tuck 29	Sullivan	440	130
Friar Tuck 81	Sullivan	96	22
Friar Tuck 120	Greene	630	NA
Midwest 7D/SW9	Pike	250	<5
Minnehaha	Sullivan	NA	72

Table 18. Comparison of total REE concentration to aluminum concentration and specific conductivity in gob seeps and spoil ridge seep.

Site	REE/Al in μg/L/ mg/L, respectively	Specific conductivity μS/cm
Alcoa (gob)	4.09	15,100
Friar Tuck (gob)	4.23	9,980–21,100
Green Valley A (gob)	2.95	7,080–35,900
Green Valley B (gob)	2.32	21,500–25,270
Blackfoot (spoil ridges)	11.9	3,710–4,710

While numerous gob piles exist at abandoned sites throughout the coal mine district of Indiana, only a small number have been evaluated for REEs. The results are promising in the amount of REEs mobilized in the gob piles, as shown in Table 16, based on data collected in 2012.

The size of the gob pile determines the flow rate and mineral content of the seep. Most gob piles are less than 1 acre in size and therefore have low flow rates (less than 5 gallons per minute). In addition to REEs, gob pile seeps contain significantly high concentrations of other dissolved elements that would require separation in an on-site REE collection system. In addition to Al in the hundreds to thousands of ppm or mg/L, some of the more concentrated components include iron in the hundreds to ten-thousand ppm range, sulfate in the thousands to ten-thousands ppm range, and both calcium and magnesium in the several hundreds of ppm. Other elements occurring in the ppm range are

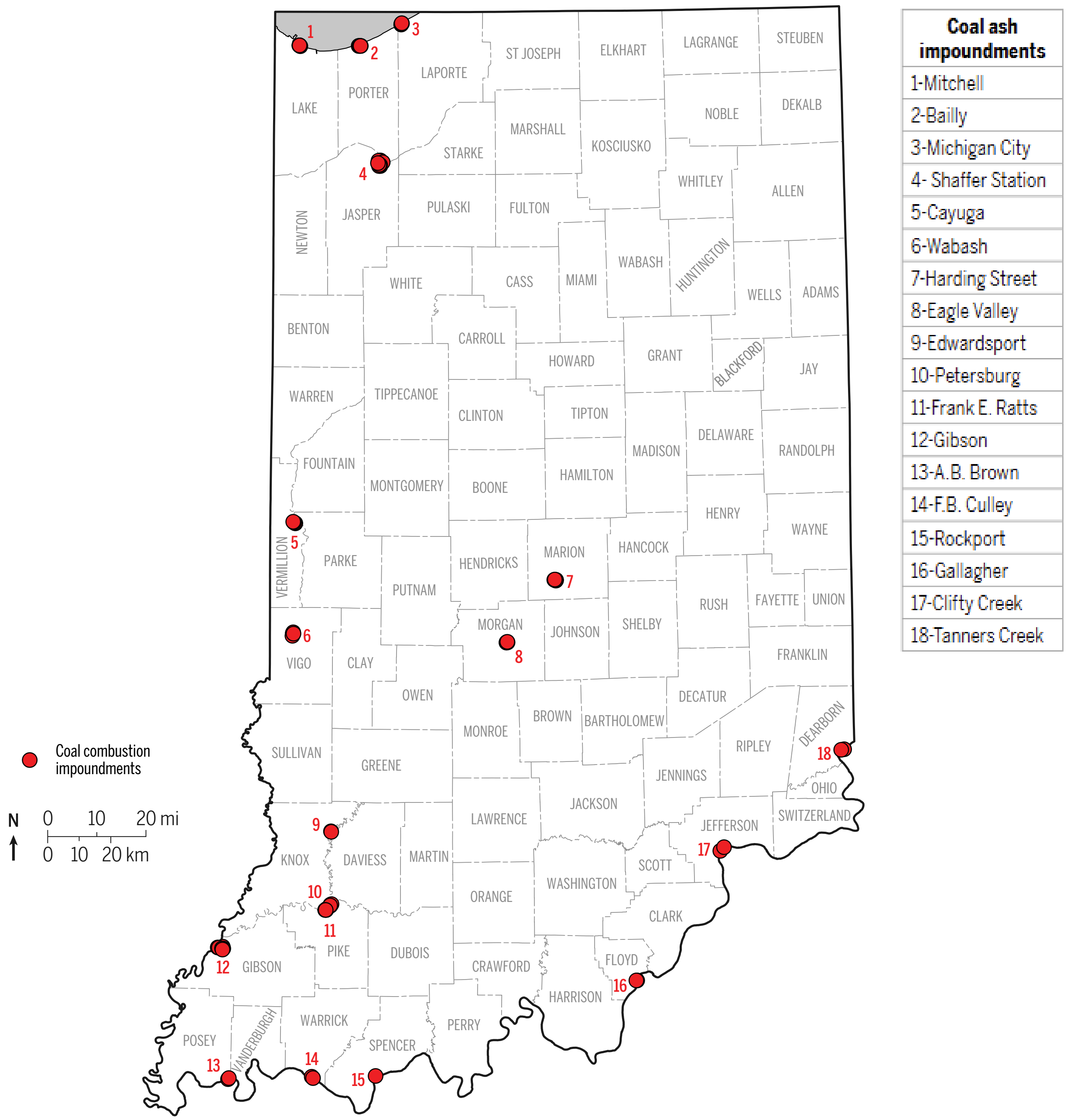


Figure 18. Map of coal ash impoundments in Indiana. From Mastalerz and others (2022b).

manganese, zinc, nickel, silicon, and sodium. Of the few other gob pile seeps for which chemical data have been collected (but not REEs), using the aluminum concentration as a proxy, a range of potential REE contents is possible as shown in Table 17.

The location of coal preparation plants shown in figure 9 (section 2.2.1) is a good reference for how many and where gob piles occur within the coal mine district of Indiana. Given that so few have been evaluated to date, it is highly likely that several more are discharging potentially economical quantities of REEs.

2.2.4 Spoil ridges

Another potential source of REEs from AMD seeps and streams is spoil ridges. While spoil ridges do not contain as many total dissolved minerals as gob pile seeps, one location that has been examined for REEs contains significant amounts, and if it is coupled with a higher flow rate, the potential economic importance should not be underestimated. This stream, a combination of three spoil ridge AMD seeps in the abandoned Blackfoot mine site, is run through a large sulfate-reducing bioreactor. The flow rate of these combined seeps is in the range of 80–100 gallons per minute. The total REE concentration

Table 19. Compilation of coal ash impoundments, their areas, and the volumes of coal ash at individual sites. For site locations, see figure 18.

Coal ash impoundments	Company	Area (acres)	Volumes of ash (m^3)
1-Mitchell	NiSource	8.3	152,375.90
2-Bailly	NIPSCO	19.51	76,523.60
3-Michigan City	NIPSCO	15	130,739.00
4-Shaffer Station	NiSource	116.2	960,468.30
5-Cayuga	Duke Energy	250.5	8,169,738.10
6-Wabash	Duke Energy	283.2	5,636,693.10
7-Harding Street	Indiana Power & Light	102.4	283,691.40
8-Eagle Valley	Indiana Power & Light	84.2	2,182,410.20
9-Edwardsport	Duke Energy	12.76	gasification slag
10-Petersburg	Indiana Power & Light	150.1	4,357,966.40
11-Frank E. Ratts	Hoosier Energy	57	175,847.80
12-Gibson	Duke Energy	423	15,742,771.20
13-A.B. Brown	Vectren	156	4,687,333.00
14-F.B. Culley	S IN Gas and Electric	43	1,010,222.50
15-Rockport	American Electric Power	111.1	390,687.90
16-Gallagher	Duke Energy	158.5	5,828,676.80
17-Clifty Creek	IN-KY Electric Corporation	115	2,633,561.90
18-Tanners Creek	Indiana Michigan Power	91.4	246,446.80

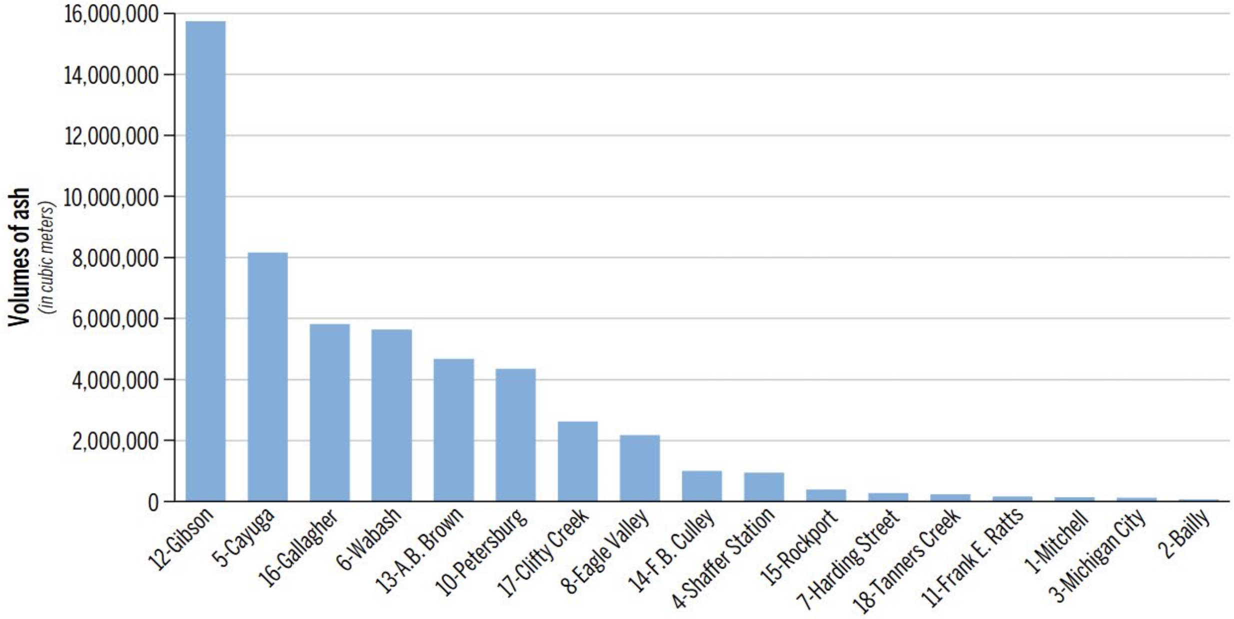


Figure 19. Bar graph showing quantities of coal ash in the largest coal ash impoundments in Indiana. Numbers preceding site names correspond to the list in Table 19. From Mastalerz and others (2022b).

measured in 2012 was 2,320 µg/L. Using the format for calculating potential quarterly yields shown in Table 12, this level of concentration and flow would produce between 200 and 250 pounds of total REEs per quarter. While the total REE concentration is well above the 1,000 µg/L threshold used to determine the best proxy (see Table 11), the aluminum content is much lower than that found in gob piles (Tables 16, 17), ranging from 100 to 190 mg/L. Table 18 shows the ratio of REEs in micrograms per liter to aluminum in milligrams per liter and the specific conductivity (a useful indicator of water contamination) ranges for four gob piles and one spoil ridge seep for which data exist.

These data (Table 18) suggest that elevated REE concentrations in acid seeps originating from spoil ridges may be more economically viable because of the lower concentrations of non-REE elements in the acid stream from which REEs are extracted. In 1998, 23 spoil ridge seeps in Pike County, Ind., were analyzed for AMD components at the Indiana Geological and Water Survey. The results included a pH range of 2.4 to 6.4, with a median value of 3.1; a specific conductivity range of 800 to 7,118 µS/cm with an average of 3,364 µS/cm; and an aluminum concentration range of 0 to 359 ppm, with an average of 93 ppm. This is a source well worth exploring, as several of the Pike County spoil ridge seeps have similar conductivities and aluminum concentrations to the Blackfoot spoil ridge seep, and estimated flow rates varying from 10 to 150 gallons per minute. Spoil ridges are typically much larger and more numerous than gob piles. While not all spoil ridges are acidic, those that are have the potential to produce more REEs over a longer period. A potential barrier to exploring the potential REE production from spoil ridge seeps is that most of the ones that have been analyzed for aluminum in Indiana are generally located further from access roads than other types of coal wash waste piles.

2.3 Post-combustion coal waste (coal ash) as a source of REE-CM

Upon combustion of coal, the organic matter releases a large amount of heat and produces gaseous products, whereas the mineral fraction forms a solid residue. This solid residue includes fly ash, bottom ash, boiler slag, and gypsum (from limestone-based flue gas desulphurization, FGD). Assuming that on average, coal used in an Indiana coal-fired power plant has ~10 % mineral matter, then ~10 % of the weight of the coal feed used in the boiler remains as coal ash after combustion. This results in large volumes of coal ash produced in states that have coal-fired power plants. For example, in 2022, Indiana coal-fired power plants produced 6.6 million tons of coal ash, and 5 million tons yearly on average (American Coal Ash Association, 2023).

2.3.1 Quantities of coal ash in Indiana

Figure 18 shows the locations of coal ash sites in Indiana, and Table 19 and figure 19 present our compilation of the areas and volumes of coal ash at individual sites. In total, according to this compilation, coal ash deposits occupy ~2,184 acres, storing ~52,566,153 m^3 of ash (Mastalerz and others, 2022b). We note that the data for individual sites come from various sources (mostly the site closure reports of multiple companies) and present our best estimates at this time. In addition, the volumes of ash change as a result of the beneficial use or displacement of the material in response to EPA regulations.

2.3.2 Coal ash composition

The composition of coal ash has been well researched worldwide, to a large extent because of environmental concerns (e.g., Silva and others, 2012; Saikia and others, 2021). In Indiana, Mastalerz and others (2004) studied relationships between the properties of the low-sulfur Danville Coal and the high-sulfur Springfield Coal and their corresponding ashes. From the baghouse ash collection system, Danville Coal ash yield ranged from 64.4 to 98.1 wt %, and carbon (C) content ranged from 0.84 to 22.73 wt %. Sulfur (S) content ranged from 0.19 to 0.29 wt %. SiO_2 ranged from 54.5 to 63.7 wt % and Al_2O_3 from 21.7 to 25.8 wt %. Fly ash from the high-sulfur Springfield Coal contained more than 95 % ash and about 3 % C. Sulfur content ranged from 0.66 to 0.80 wt %, higher than in the Danville ash. SiO_2 ranged from 40.5 to 44.6 and Al_2O_3 ranged from 17 to 19.6 wt %. Mastalerz and others (2004) concluded that the properties of fly ash from these coals reflect the properties of the feed coal, as well as local combustion (e.g., temperature) and post-combustion (e.g., ash collection) conditions.

Among unconventional sources, coal ash has been suggested as one of the more promising sources for REEs (Hower and others, 2020; Pan and others, 2020). Kolker and others (2017) indicated that these elements were concentrated in the glass phase, the most abundant component of coal fly ash, and suggested that this fraction should be especially targeted for further concentration and extraction. Association of REEs with mineral matter in numerous coals worldwide (Dai and Finkelman, 2018) and commonly mentioned positive correlations between Al and REEs (Kolker and others, 2017; 2021). Indeed they point to coal ash deposits as a promising source of REEs. For the coal ash produced in Indiana, not many publicly available data exist on REEs concentrations. Table 20 shows analyses of two coal ashes from an Indiana plant, compared with the average values of the coal. These examples show notable enrichment, indicating critical mineral potential, provided they could be utilized economically. The DOE estimated the economic viability threshold for REEs at 300 ppm (U.S. DOE NETL, 2017), and the values shown in Table 20 (859 and 706 ppm) far exceed that threshold. Considering the large volume of coal ash in Indiana (Table 19), this material is indeed a promising source of critical minerals.

2.4 Metalliferous black shales (Pennsylvanian and Devonian) as potential sources of critical metals such as V, Zn, and Pb

Black shales are organic matter-rich, fine-grained sedimentary rocks. They are not only important source rocks of conventional and unconventional petroleum systems (Tissot and Welte, 1984; Mastalerz and others, 2013) but they also host a variety of trace metals (Schultz, 1991; Leventhal, 1993; Coveney, 2003). In Indiana, Pennsylvanian and Devonian black shales are potential hosts of REE-CM (Mastalerz and others, 2022a).

2.4.1 Pennsylvanian black shales

Pennsylvanian black shales are rich in organic matter, typically ranging from 4 to 40 % (Hatch and Leventhal, 1985; Wenger and Baker, 1986; Coveney and Glascock, 1989; Mastalerz and others, 2022a). These black shales have long been known to be enriched in various metals, such as V, Zn, Mo, or U (Runnels and others, 1953; Ostrom and others, 1955; Swanson, 1961; Zangerl and Richardson, 1963; Coveney, 1979; Coveney and Glascock, 1989). Mastalerz and others (2022a) studied the element concentrations of Pennsylvanian black shales and found that six marine shale horizons have the highest potential for REE-CM. They are the Anna Shale Member and Turner Mine Shale Member of the Dugger Formation, Excello Shale Member of the Petersburg Formation, Mecca Quarry Shale Member of the Linton Formation, and Logan Quarry Shale Member and Veale Shale of the Tradewater Formation (fig. 7).

The average As content in the Pennsylvanian shales ranges from 21.80 to 47.42 ppm (fig. 20), values much higher than the 4.8 ppm in the upper continental crust (UCC; Rudnick and Gao, 2014). The highest average value was recorded for the Logan Quarry Shale (47.42 ppm).

The Pennsylvanian shales are rich in Ni, with average contents ranging from 230.50 ppm in the Anna Shale to 321.11 ppm in the Veale Shale (fig. 21), compared to 47 ppm in the UCC (Rudnick and Gao, 2014).

The V content of the Pennsylvanian shales is also highly enriched, with average values ranging from 467.30 ppm in the Anna Shale to 1241.65 ppm in the Mecca Quarry Shale (fig. 22), compared to 97 ppm in the UCC (Rudnick and Gao, 2014). Previous X-ray diffraction (XRD), scanning electron microscope (SEM), and transmission electron microscopy (TEM) studies of the Mecca Quarry Shale showed that the majority of V (~65 %) is hosted by illite, and the remaining portion is associated with organic matter (Peacor and others, 2000).

Table 20. REE concentrations in two coal ash samples from Indiana. Light REE = La+Ce+Pr+Nd+Sm+Eu+Gd; heavy REE = Tb+Dy+Ho+Er+Tm+Yb+Lu. Values for average concentrations in hard coal are included for comparison.

Component	104 1-day ash (ash basis)	105 1-week ash (ash basis)	Coal (whole-rock basis)
Rare earth elements			
Sc (ppm)	42	39	4
La (ppm)	147	118	10
Ce (ppm)	310	248	22
Pr (ppm)	36	26	3.5
Nd (ppm)	141	113	11
Sm (ppm)	29	24	1.9
Eu (ppm)	6	5	0.5
Gd (ppm)	25	21	2.6
Tb (ppm)	3	3	0.32
Dy (ppm)	17	16	2
Ho (ppm)	3	3	0.5
Er (ppm)	9	8	0.85
Tm (ppm)	1	1	0.31
Yb (ppm)	8	8	1
Lu (ppm)	1	1	0.19
Y (ppm)	75	68	8.6
REE+Y+Sc (ppm)	859	706	62–68
Light REE (ppm)	696	558	variable
Heavy REE (ppm)	44	40	variable
Other selected critical elements			
As (ppm)	62	55	7.6–9
Ga (ppm)	60	54	5.5–6.0
Ge (ppm)	121	104	2–2.4
Ni (ppm)	598	507	9–17
V (ppm)	327	329	22–28
Zn (ppm)	608	618	3–125

The Pennsylvanian shales are highly enriched in Zn. The average contents range from 428.50 ppm in the Logan Quarry Shale to 1,442.70 ppm in the Veale Shale. The Veale Shale is the most enriched in Zn, with some samples having contents as high as 6,399 ppm

	Arsenic (ppm)		
	Min	Max	Average
Anna Shale	8	32	21.80
Turner Mine Shale	18	54	29.46
Excello Shale	17	169	36.65
Mecca Quarry Shale	14	89	35.81
Logan Quarry Shale	15	84	47.42
Veale Shale	17	213	40.27
UCC			4.8

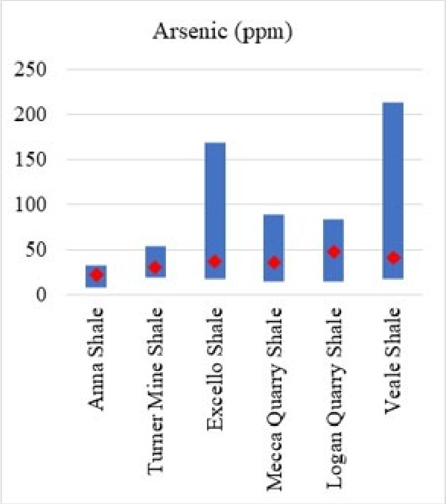


Figure 20. Table data and bar graph showing arsenic content (range and average) in the Pennsylvanian black shales. UCC – upper continental crust.

	Nickel (ppm)		
	Min	Max	Average
Anna Shale	100	385	230.50
Turner Mine Shale	48	412	235.46
Excello Shale	53	536	275.44
Mecca Quarry Shale	53	804	306.10
Logan Quarry Shale	47	455	224.08
Veale Shale	32	784	321.11
UCC			47

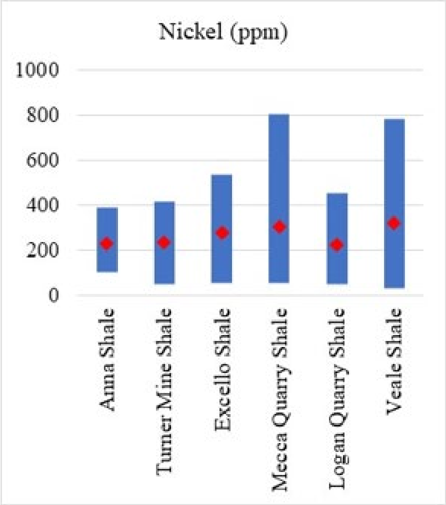


Figure 21. Table data and bar graph showing nickel content (range and average) in the Pennsylvanian black shales. UCC – upper continental crust.

	Vanadium (ppm)		
	Min	Max	Average
Anna Shale	131	1,740	467.30
Turner Mine Shale	186	2,477	817.73
Excello Shale	58	2,047	1,081.88
Mecca Quarry Shale	233	2,770	1,241.65
Logan Quarry Shale	174	919	533.33
Veale Shale	61	2,190	838.30
UCC			97

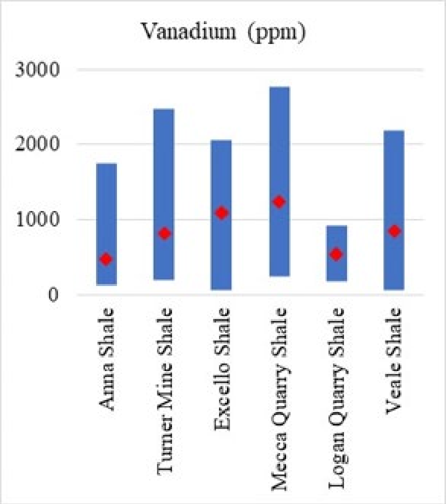


Figure 22. Table data and bar graph showing vanadium content (range and average) in the Pennsylvanian black shales. UCC – upper continental crust.

	Zinc (ppm)		
	Min	Max	Average
Anna Shale	91	3,610	900.90
Turner Mine Shale	41	2,492	820.81
Excello Shale	31	3,204	1,063.91
Mecca Quarry Shale	58	5,480	1,412.58
Logan Quarry Shale	89	1,168	428.50
Veale Shale	20	6,399	1,442.70
UCC			67

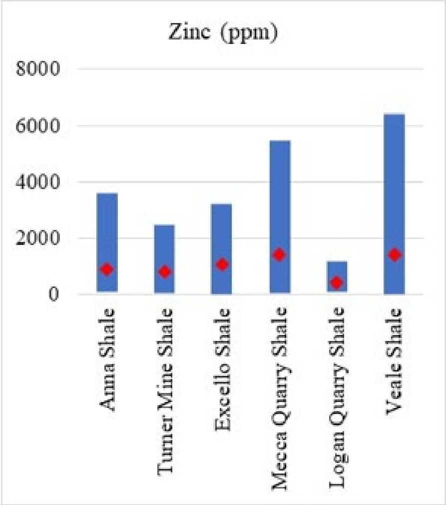


Figure 23. Table data and graph showing zinc content (range and average) in the Pennsylvanian black shales. UCC – upper continental crust.

(fig. 23). Mastalerz and Drobniak (2007) suggested that Zn was associated with sphalerite.

The average concentrations of REEs in the Pennsylvanian shales vary from 176.89 ppm in the Excello Shale to 354.93 ppm in the Logan Quarry Shale (fig. 24A). Average content of heavy REE (Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu+Y) of the Pennsylvanian shales does not exceed 100 ppm, and the content of light REE (La+Ce+Pr+Nd+Pm+Sm+Eu) ranges from 122.78 to 243.47 ppm (fig. 24 B, C). Some samples of the Logan Quarry Shale have heavy REE content of more than 300 ppm (fig. 24C). Published data generated from coal combustion waste suggested that a combined REE oxides content above 1,000 ppm (on ash basis) could be considered the threshold for beneficial recovery of REE (Seredin, 2004; Seredin and Dai, 2012). Considering similar criteria for these shales, the studied samples would place below this threshold.

The Pennsylvanian shales are characterized by high U content, averaging from 39.05 ppm for the Turner Mine Shale to 87.03 ppm for the Veale Shale (fig. 25). All these values are highly enriched compared to 2.7 ppm in UCC (Rudnick and Gao, 2014). Uranium in marine black shales is typically associated with organic matter but also can be incorporated into sedimentary phosphate (Swanson, 1961).

In the Pennsylvanian shales, Mo concentration is high, in numerous samples exceeding 1,000 ppm (fig. 26). The Mecca Quarry Shale is the most enriched in Mo (average 640.10 ppm, maximum 1,620 ppm), followed by the Veale Shale (537.30 ppm, maximum 1,940 ppm). Such a high Mo content in these marine shales is likely a result of the combination of favorable anoxic depositional and diagenetic conditions and additional enrichment by Mo-bearing fluids of the Mississippi Valley type that invaded the Illinois Basin in the Paleozoic or later (Hatch and others, 1976; Coveney and others, 1987).

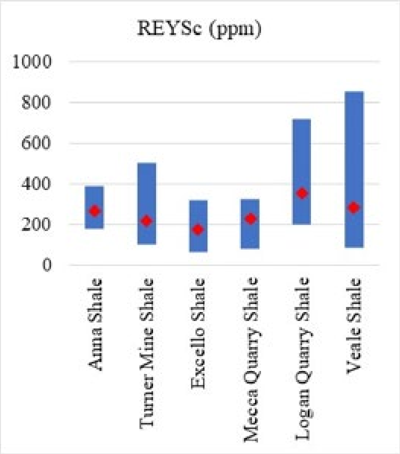
Table 21 summarizes the average concentrations of critical elements and their enrichment factors relative to UCC values. As, Ni, V, and Zn are all enriched, with Zn reaching up to 20 enrichment factor in the Mecca Quarry Shale. Overall, the Excello Shale, Mecca Quarry Shale, Logan Quarry Shale, and Veale Shale have higher critical mineral potential than the Anna Shale and Turner Mine Shale. In contrast, REEs are either not enriched, being similar to the values of the UCC, or are enriched very slightly.

Cadmium, Cr, Cu, Mo, and U enrichment factors are listed in Table 22. Cd, Mo, and U are especially enriched compared to the UCC. The Excello Shale, Mecca Quarry Shale, Logan Quarry Shale, and Veale Shale have higher average and maximum U and Mo concentrations than the Anna Shale and Turner Mine Shale.

The Pennsylvanian black shales generally overlie coal beds and are relatively thin. For example, The Excello Shale in Indiana occurs within the depth range from very shallow in Clay, Greene, Daviess, Pike and Warrick Counties to > 1,000 ft in Posey County (fig. 27). Its thickness ranges from 0.2 to 8 ft, but is mostly within the range of 1 to 4 ft (fig. 28). Greater thickness is usually of very local scale. The Mecca Quarry depth trend expectedly follows that of the Excello Shale, reaching > 1,100 ft in Posey County (fig. 29). Similar to the Excello Shale, the thickness of the Mecca Quarry Shale reaches 1 to 4 ft in most places (fig. 30). As to the potential utilization of these shales as sources of metals, for both shales, Clay, Greene, Daviess, Pike, and Warrick Counties would be most suitable because deposits are shallow and easily accessible.

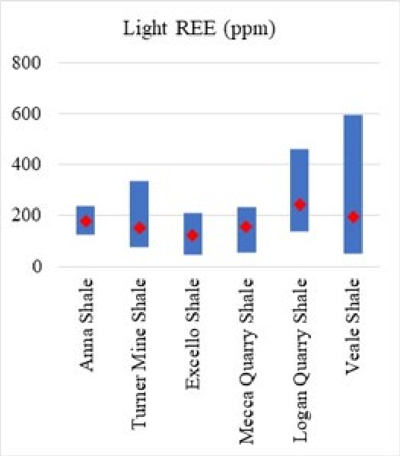
A

	REYSc (ppm)		
	Min	Max	Average
Anna Shale	177.45	392.77	267.86
Turner Mine Shale	104.72	505.59	218.51
Excello Shale	63.73	322.32	176.89
Mecca Quarry Shale	81.05	323.49	228.63
Logan Quarry Shale	199.44	720.38	354.93
Veale Shale	86.38	854.68	285.13
UCC			183.14



B

	Light REE (ppm)		
	Min	Max	Average
Anna Shale	123.79	237.74	177.26
Turner Mine Shale	76.2	337.11	153.41
Excello Shale	44.71	208.94	122.78
Mecca Quarry Shale	56.37	233.1	156.63
Logan Quarry Shale	137.46	460.25	243.47
Veale Shale	49.89	594.65	195.70



C

	Heavy REE (ppm)		
	Min	Max	Average
Anna Shale	37.66	144.03	76.10
Turner Mine Shale	13.78	155.48	50.69
Excello Shale	9.02	98.38	42.02
Mecca Quarry Shale	19.68	113.45	58.04
Logan Quarry Shale	31.86	325.36	94.04
Veale Shale	28.49	243.03	74.47

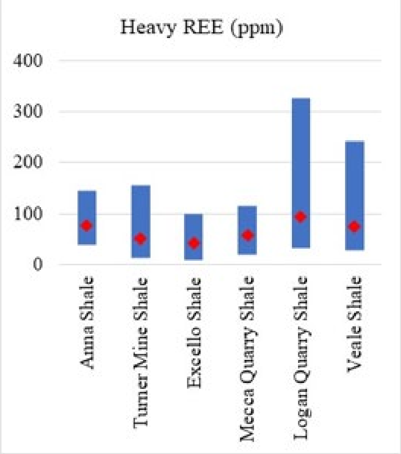


Figure 24. Table data and bar graphs showing REE concentrations (A-total, B-light, and C-heavy) in the Pennsylvanian black shales studied. Heavy REE (Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu+Y), light REE (La+Ce+Pr+Nd+Pm+Sm+Eu), REYSc (REE+Y+Sc). UCC – upper continental crust.

	Uranium (ppm)		
	Min	Max	Average
Anna Shale	13.44	120	40.69
Turner Mine Shale	6.88	131	39.05
Excello Shale	3.68	179	52.23
Mecca Quarry Shale	10.42	235	84.68
Logan Quarry Shale	4.33	269	53.26
Veale Shale	2.23	398	87.03
UCC			2.7

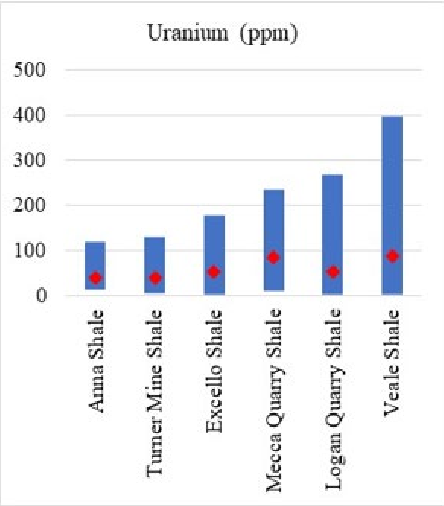


Figure 25. Table data and graph showing uranium content (range and average) in the Pennsylvanian black shales. UCC – upper continental crust.

	Molybdenum (ppm)		
	Min	Max	Average
Anna Shale	9	135	50.70
Turner Mine Shale	<2	648	203.68
Excello Shale	4	1,178	405.19
Mecca Quarry Shale	3	1,620	640.10
Logan Quarry Shale	3	1,090	262.17
Veale Shale	3	1,940	537.30
UCC			1.1

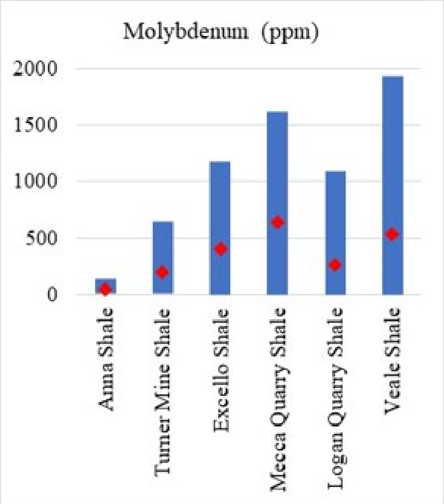


Figure 26. Table data and graph showing molybdenum content (range and average) in the Pennsylvanian black shales. UCC – upper continental crust.

2.4.2 Devonian shales

The Devonian-Mississippian New Albany Shale is the major source rock of oil and gas in the Illinois Basin. The New Albany Shale is dominantly within the oil window, with the Hicks Dome area in southern Illinois reaching the gas window (Mastalerz and others, 2013). Commercial gas production from the New Albany Shale began as early as 1863 from the Moreman well drilled in Meade County, Ky. (Hasenmueller and Comer, 1994).

The average TOC content of the New Albany Shale is 6–7 wt. %, ranging from < 1 to 20 wt. % (Liu and others, 2019). The average U, Mo, As, Ni, V, Zn, and REE contents of the New Albany Shale based on 100 samples are 40.3, 129.1, 37.3, 144.4, 330.8, 312.8, and 248.0 ppm, respectively. The Falling Run Bed, a phosphatic bed at the top of the New Albany Shale, is rich in REEs; one sample has a REEs content of 2,739.73 ppm. More samples are needed to confirm the REE potential of this bed. The bed is very thin, typically 1–5 inches thick. Overall, the New Albany Shale is not as metalliferous as the Pennsylvanian black shales. In addition, the New Albany Shale is buried deeper, thus less accessible, than the Pennsylvanian black shales. Therefore, the Devonian New Albany Shale has less REE-CM potential than Pennsylvanian black shales.

2.5 Pennsylvanian paleosols as sources of REEs, lithium (Li), gallium (Ga), and germanium (Ge)

Paleosols are ancient soils preserved in the rock record. They are common in coal-bearing sedimentary basins and represent periods of aerial exposure before the

Table 21. Average critical element concentration and their enrichment factors (EF) in the Pennsylvanian black shales. EF is calculated relative to UCC values. REYSc (REE+Y+Sc). UCC – upper continental crust.

Element/ Shale	As (ppm)	As EF	Ni (ppm)	Ni EF	V (ppm)	V EF	Zn (ppm)	Zn EF	REYSc (ppm)	REYSc EF
Anna	21.8	4.5	230.5	4.9	467.3	4.8	900.9	13.4	267.86	1.5
Turner Mine	29.46	6.1	235.46	5	817.73	8.4	820.81	12.3	218.51	1.2
Excello	36.65	7.6	275.44	5.9	1,081.88	11.2	1,063.91	15.9	176.89	1
Mecca Quarry	35.81	7.5	306.1	6.5	1,241.65	12.8	1,412.58	21.1	228.63	1.2
Logan Quarry	47.42	9.9	224.08	4.8	533.33	5.5	428.5	6.4	354.93	1.9
Veale	40.27	8.4	321.11	6.8	838.3	8.6	1,442.7	21.5	285.13	1.6
UCC	4.8		47		97		67		183.14	

Table 22. Average concentrations of other selected elements and their enrichment factors (EF) in the Pennsylvanian black shales. EF is calculated relative to UCC values. UCC – upper continental crust.

Element/ Shale	Cd (ppm)	Cd EF	Cr (ppm)	Cr EF	Cu (ppm)	Cu EF	Mo (ppm)	Mo EF	U (ppm)	U EF
Anna	47.7	530	501.3	5.4	123.4	4.4	50.7	46.1	40.69	15.1
Turner Mine	43.22	480.2	377.65	4.1	107.88	3.9	203.68	185.2	39.05	14.5
Excello	48.16	535.1	272.77	3	106.37	3.8	405.19	368.4	52.23	19.3
Mecca Quarry	44.86	498.4	250.26	2.7	122.84	4.4	640.1	581.9	84.68	31.4
Logan Quarry	11.26	125.1	171.75	1.9	77.25	2.8	262.17	238.3	53.26	19.7
Veale	54.39	604.3	242.48	2.6	101.59	3.6	537.3	488.5	87.03	32.2
UCC	0.09		92		28		1.1		2.7	

establishment of more humid conditions and development of peat mires. In the Illinois Basin, including Indiana, paleosols (known also as underclays) commonly underlie coal beds and constitute a significant component of the Pennsylvanian strata. Paleosols are clay-rich rocks and have recently received attention in relation to the search for new sources of critical minerals, and REEs and Li in particular.

In Indiana, paleosols as potential sources of REEs and Li were investigated by Mastalerz and others (2022c) and as a source of Ga and Ge by Mastalerz and Roden (2023). Paleosols under various coal beds were analyzed in several locations in southwestern Indiana (fig. 31). Their thickness ranged from 2 to 13.5 ft. The thickest paleosols were documented under the Danville Coal Member, the Houchin Creek Coal Member, and the Wise Ridge Coal Bed. See fig. 7 for the stratigraphic position of these coals.

2.5.1 Rare earth elements

Total REE content in Indiana paleosol samples ranges from 138.8 ppm to 728.6 ppm, with an average range of 208.3 ppm (Colchester paleosol) to 342.9 ppm in the paleosol under the Upper Block Coal (fig. 32). The paleosol under the Upper Block Coal has the largest variation in heavy REE content (49 to 148 ppm) and also the highest average heavy REE content (74.5 ppm) (fig. 33). Light REE dominate over heavy REE (fig. 34), and the variation in the total REEs follows that of the light REE.

Several factors must be considered when evaluating deposits as a potential source of REYs. The total REE concentration is a suitable parameter for an initial screening. Data generated on coal combustion waste suggested that a combined REE oxide content above 1,000 ppm (on ash basis), could be considered the threshold for beneficial recovery of the metals (Seredin, 2004). Seredin and Dai (2012) further suggested that this cut-off value could be lowered to 800–900 ppm, especially if the layers in consideration are thick. Considering similar criteria for paleosols, most Indiana paleosols would not satisfy values for beneficial recovery. The majority of paleosols

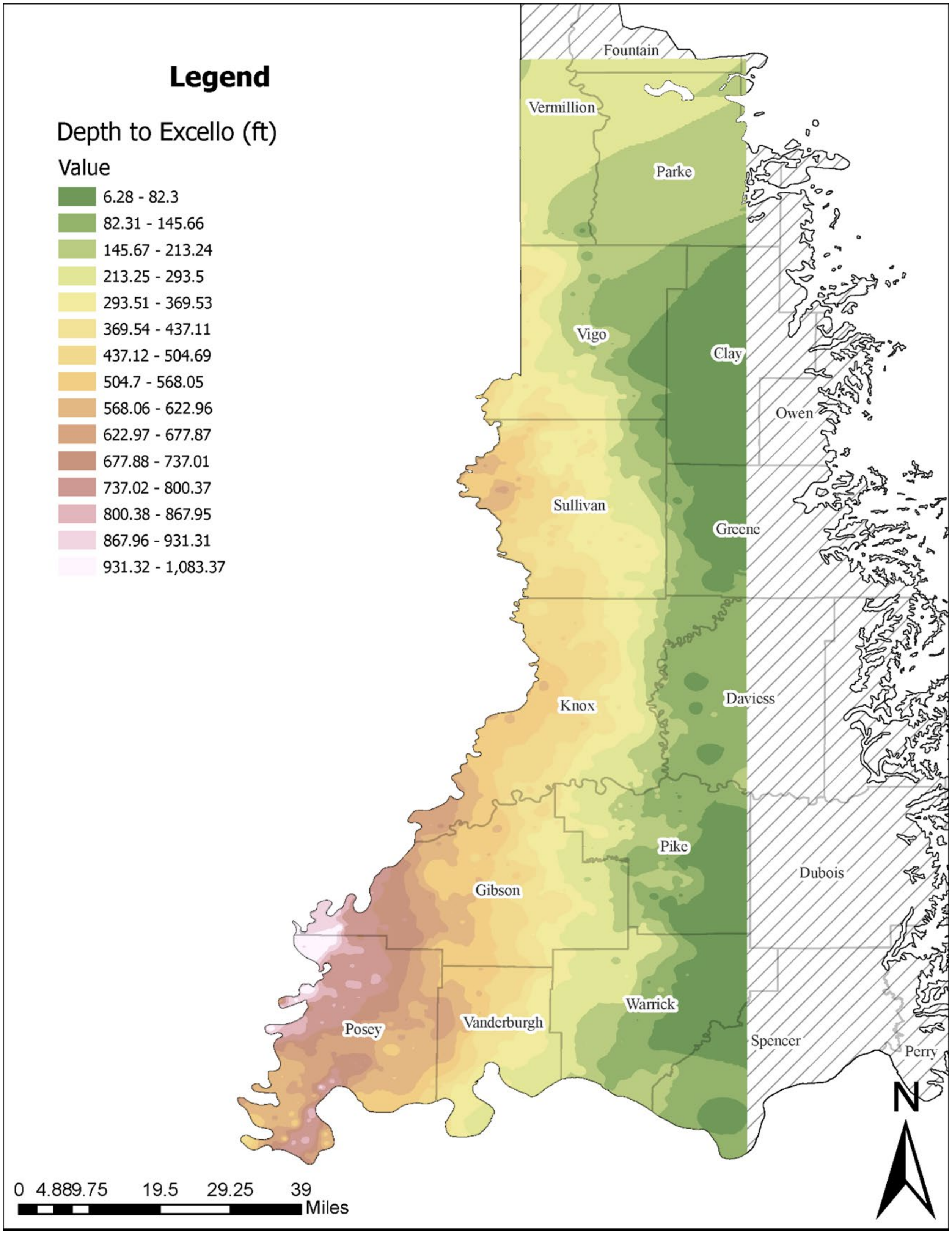


Figure 27. Structure contour (depth) map of the Excello Shale in southwestern Indiana. The depth was determined from geophysical logs. Northern and eastern extent of the Excello Shale is not defined because of data limitations along the basin edge.

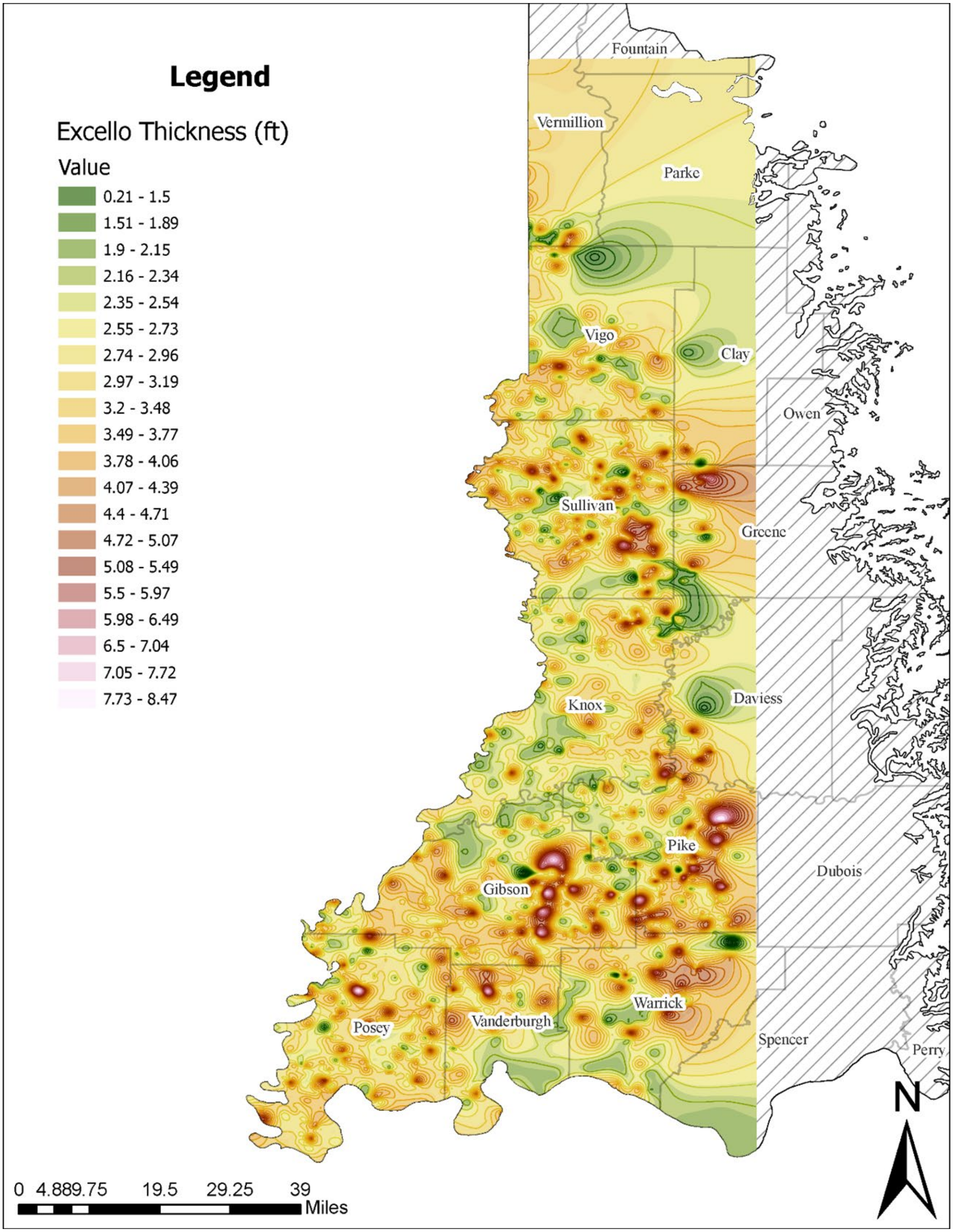


Figure 28. Isopach (thickness) map of the Excello Shale in southwestern Indiana. The thickness was determined from geophysical logs. Northern and eastern extent of the Excello Shale is not defined because of data limitations along the basin edge.

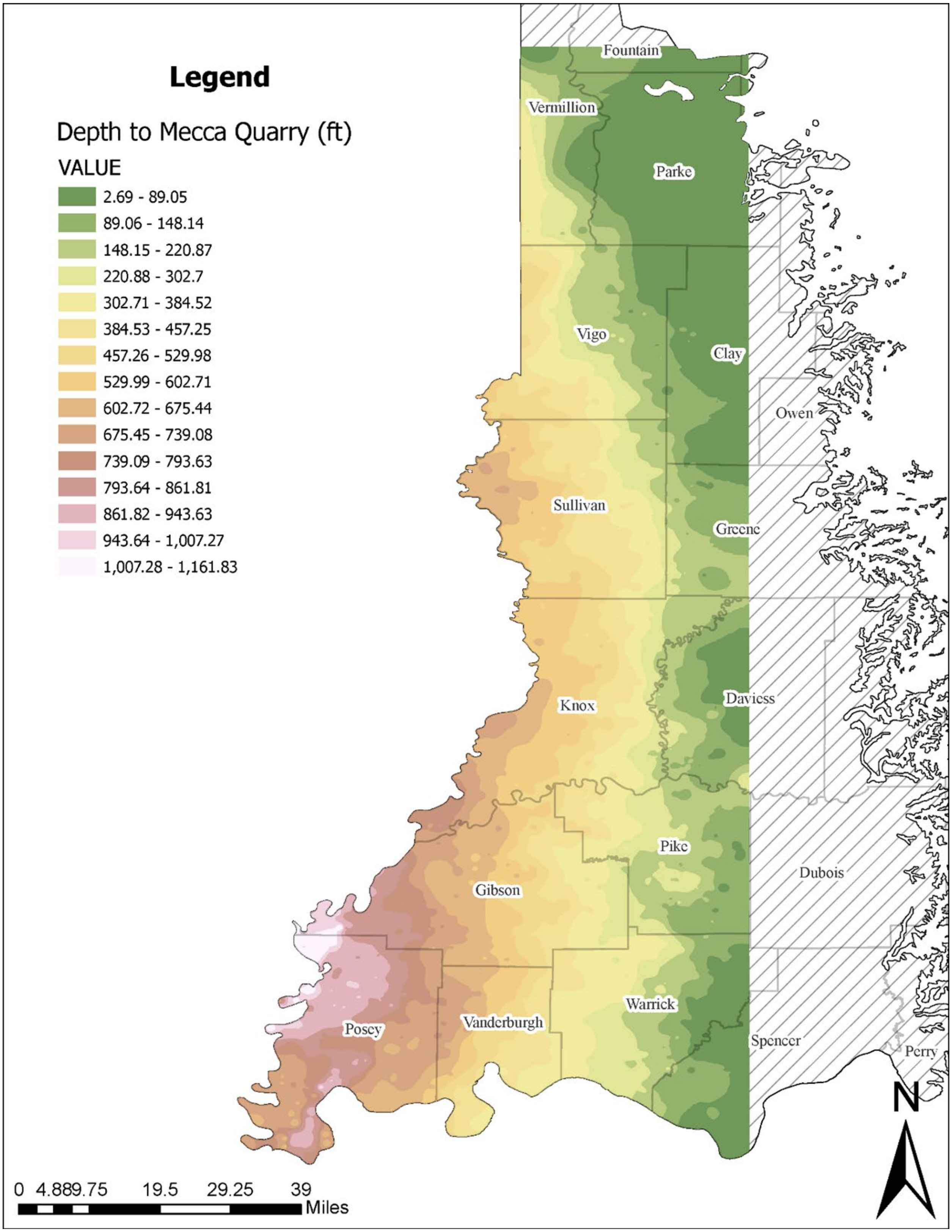


Figure 29. Structure contour (depth) map of the Mecca Quarry Shale in southwestern Indiana. The depth was determined from geophysical logs. Northern and eastern extent of the Mecca Quarry Shale is not defined because of data limitations along the basin edge.

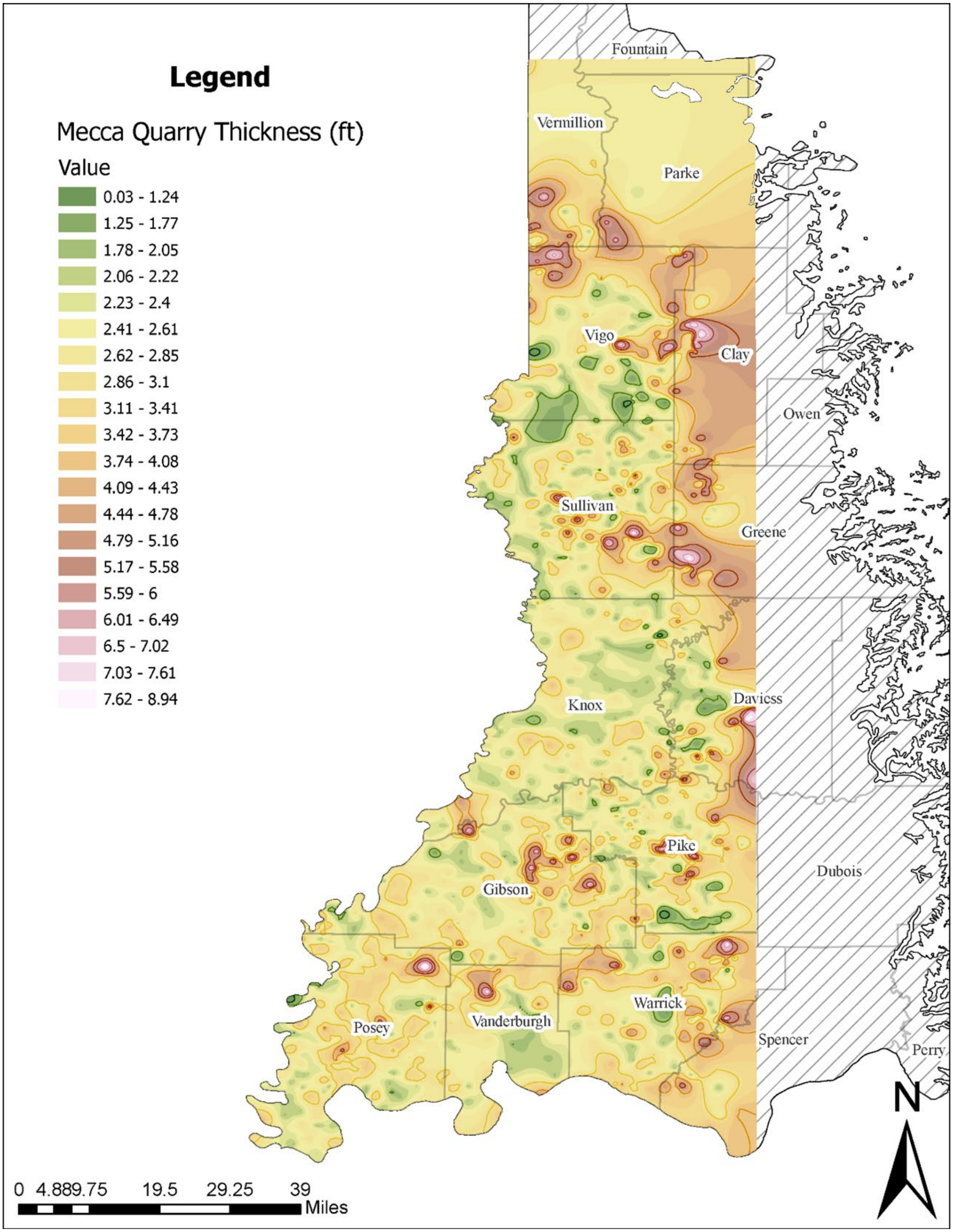


Figure 30. Isopach (thickness) map of the Mecca Quarry Shale in southwestern Indiana. The thickness was determined from geophysical logs. Northern and eastern extent of the Mecca Quarry Shale is not defined because of data limitations along the basin edge.

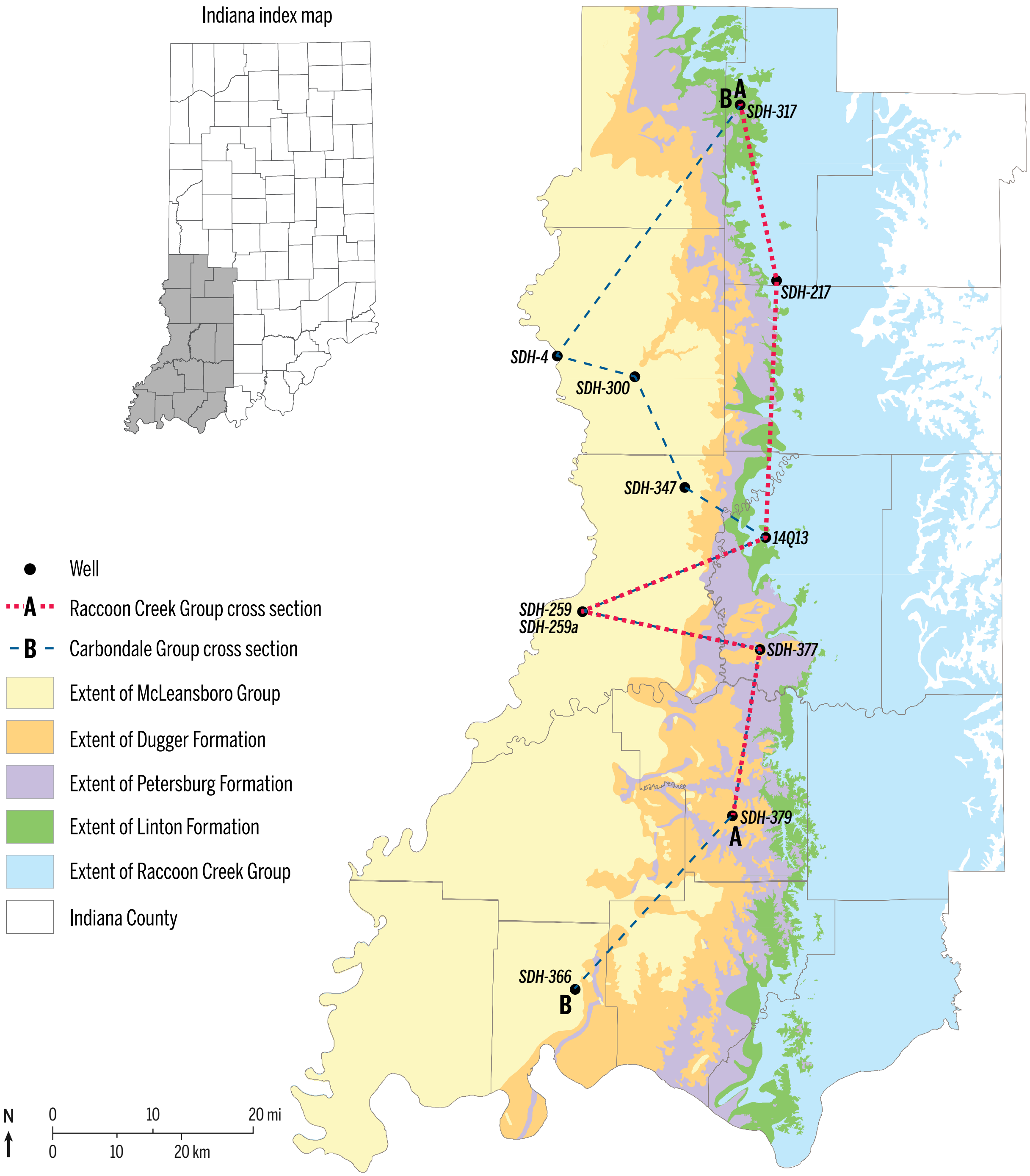


Figure 31. Bedrock geologic map with locations of cores from which paleosols were selected for analysis (from Mastalerz and others, 2022c).

	Total REE [ppm]		
	min	max	average
Maria Creek	224.3	384.8	275.6
Danville Coal	155.9	728.6	329.7
Herrin Coal	141.4	344.4	244.2
Springfield Coal	175.8	308.8	230.1
Houchin Creek Coal	129.5	318.7	243.4
Colchester Coal	138.8	286.5	208.3
Seelyville Coal	188.3	294.2	247.7
Carrier Mills Shale	230.3	404.5	328.0
Wise Ridge Coal	165.5	606.5	284.8
Viking B Coal	187.6	371.0	257.9
Upper Block Coal	264.0	635.0	342.9
Lower Block Coal	214.3	316.2	282.0

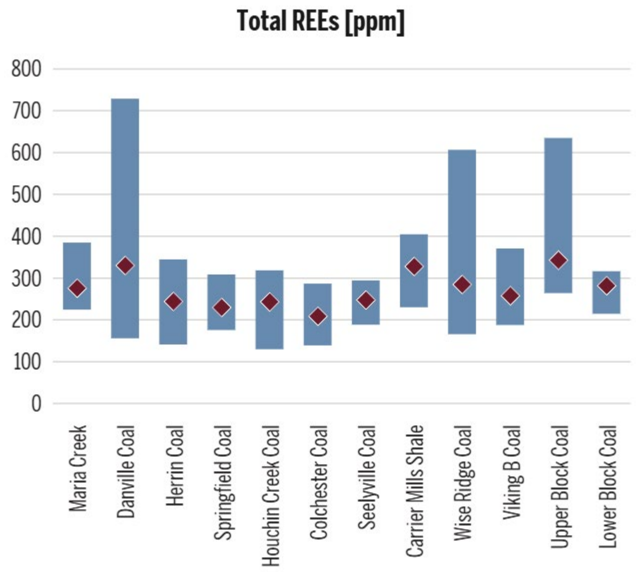


Figure 32. Table data and bar graph of total REE concentrations in the paleosols under the respective coal beds or shale horizons (from Mastalerz and others, 2022c). Viking B coal is currently formalized as the Montgomery Coal Bed and Carrier Mills shale as the Logan Quarry Shale Member (Mastalerz and others, 2024).

	Heavy REE [ppm]		
	min	max	average
Maria Creek	40.2	50.1	46.2
Danville Coal	37.2	65.4	51.1
Herrin Coal	36.9	80.0	50.7
Springfield Coal	41.1	59.8	48.4
Houchin Creek Coal	32.1	63.1	47.0
Colchester Coal	33.5	67.1	47.2
Seelyville Coal	39.7	59.6	48.8
Carrier Mills Shale	47.2	57.0	51.6
Wise Ridge Coal	41.5	67.9	54.6
Viking B Coal	43.4	55.5	50.1
Upper Block Coal	49.0	148.0	74.5
Lower Block Coal	51.6	66.0	61.0

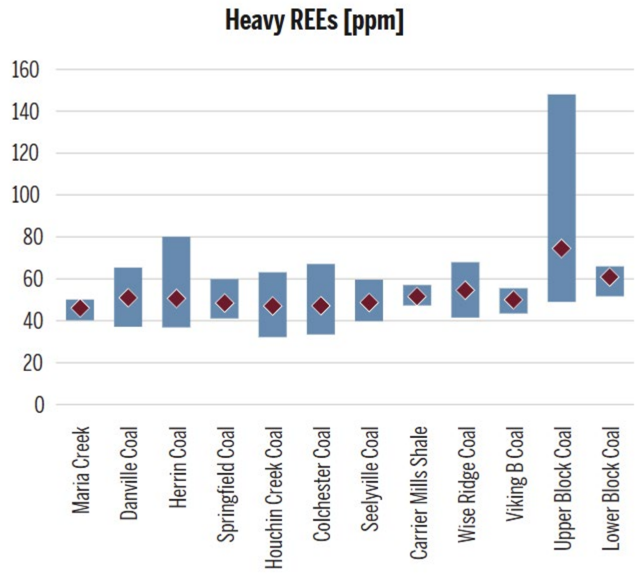


Figure 33. Table data and bar graph of heavy REE concentrations in the paleosols under the respective coal beds or shale horizons (from Mastalerz and others, 2022c). Heavy REE (Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu+Y). Viking B coal is currently formalized as the Montgomery Coal Bed and Carrier Mills Shale as the Logan Quarry Shale Member (Mastalerz and others, 2024).

	Light REE [ppm]		
	min	max	average
Maria Creek	174.3	338.6	229.4
Danville Coal	113.2	665.0	278.7
Herrin Coal	104.5	289.2	193.5
Springfield Coal	134.7	249.0	181.6
Houchin Creek Coal	97.4	255.7	196.4
Colchester Coal	92.0	235.0	161.1
Seelyville Coal	141.6	252.2	198.9
Carrier Mills Shale	173.3	357.3	276.4
Wise Ridge Coal	108.5	565.0	230.2
Viking B Coal	139.7	315.5	207.8
Upper Block Coal	208.0	487.0	268.4
Lower Block Coal	162.6	251.0	221.1

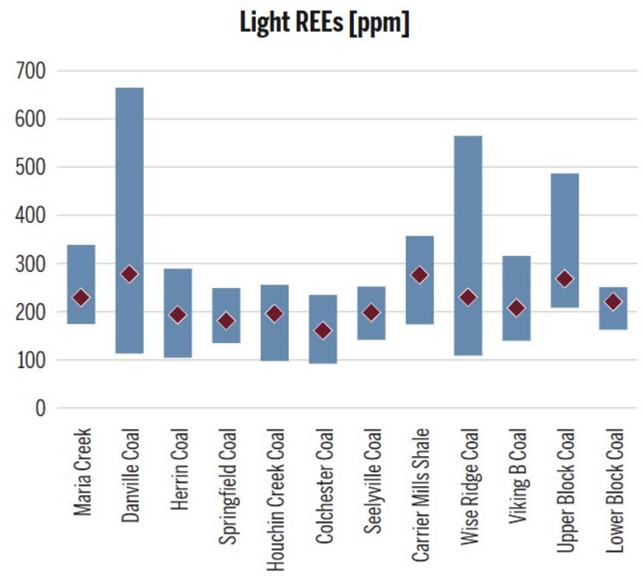


Figure 34. Table data and bar graph of light REE concentrations in the paleosols under the respective coal beds or under shale horizons (from Mastalerz and others, 2022c). Light REE (La+Ce+Pr+Nd+Pm+Sm+Eu). Viking B coal is currently formalized as the Montgomery Coal Bed and Carrier Mills Shale as the Logan Quarry Shale Member (Mastalerz and others, 2024).

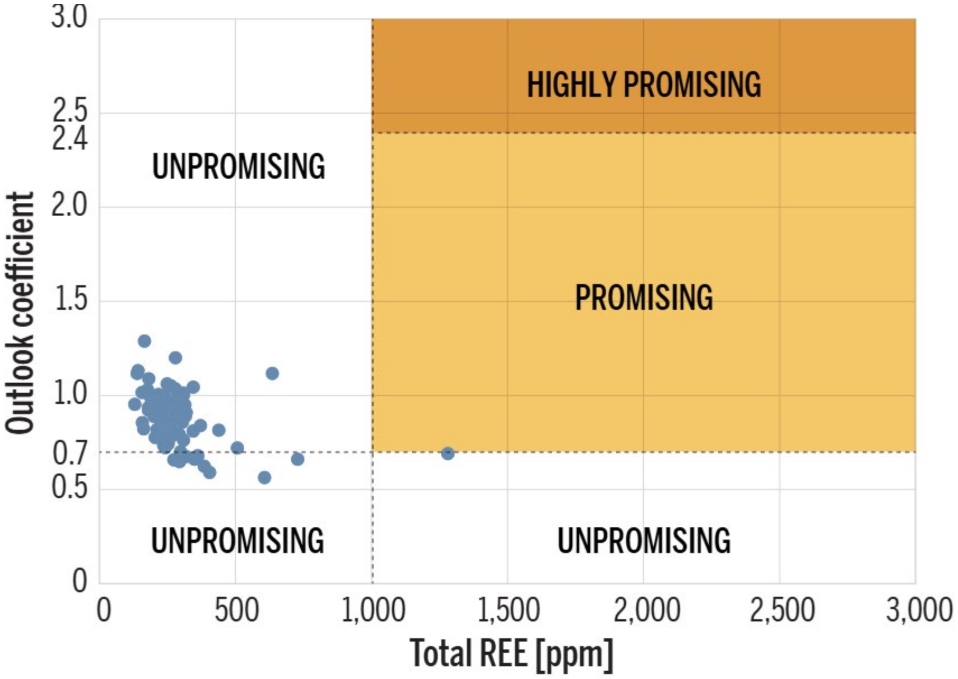


Figure 35. Scatter plot evaluating the industrial value of REE in paleosols in Indiana. From Mastalerz and others (2022c).

in Indiana have REE values that are roughly representative of the upper continental crust (UCC). Some paleosols, however, are slightly enriched (C/UCC values of 2 to 5) or enriched (C/UCC>5) and these are paleosols underlying the Danville Coal and the Upper Block Coal (Mastalerz and others, 2022c).

Another approach of evaluating REYSc potential takes into account the contribution of critical REE (most valuable) in relation to excessive (less valuable) elements: the best-quality source should have as many critical elements and as few excessive elements as possible (Seredin, 2010). This approach uses a parameter known as the "outlook coefficient" (C_{outl}) that is calculated as: C_{outl} = (Nd+Eu+Tb+Dy+ER+Y/Sum REY) / (Ce+Ho+TM+Yb+Lu/Sum REY).

The higher the C_{outl} value, the more promising the ore with respect to potential industrial value. For the paleosols studied, a combination of REE concentrations and C_{outl} is shown in figure 35. On this diagram, all samples plot in the unpromising areas because of low REE concentrations. We note, however, that the significance of this parameter may change in response to changes in REE extraction technology, prices of elements, and other factors.

Although the Indiana paleosols do not have high concentrations of REEs, the liberation of REEs by acid leaching from these clay-rich rocks should be relatively easy (e.g., Moldoveanu and Papangelakis, 2016; Yang and others, 2020), compensating for non-enriched or only slightly enriched concentrations. Especially thick paleosols with more than average REE content, such as those under the Wise Ridge Coal bed or under the Upper Block Coal Member, present good potential targets.

2.5.2 Lithium

Paleosols and other clay-rich Pennsylvanian rocks have long been known to contain relatively high, though variable, concentrations of lithium. For example, Tourtelot and Brenner-Tourtelot (1977) stated that "Flint clays and related rocks of Pennsylvanian age in Alabama, Ohio, Pennsylvania, Kentucky and Missouri very commonly contain several hundred parts per million of lithium, with maximum values as large as 4,000 to 5,100 ppm in the Missouri samples." They further suggested that these clay-rich rocks were "an unevaluated potential resource for lithium." For the paleosols in Indiana, the Li content shows a large variation, from 21 ppm to 530 ppm (fig. 36). On average, paleosols associated with the Wise Ridge Coal Bed are richest in Li (249.3 ppm), followed by the Montgomery Coal Bed (180.8 ppm). In general, paleosols under the coals of the Raccoon Creek Group have higher Li content than those under the

	Lithium [ppm]		
	min	max	average
Maria Creek	40.0	67.0	50.8
Danville Coal	45.0	258.0	115.6
Herrin Coal	25.0	129.0	76.0
Springfield Coal	29.0	118.0	51.1
Houchin Creek Coal	21.0	205.0	83.7
Colchester Coal	56.0	118.0	84.0
Seelyville Coal	39.0	205.0	85.8
Carrier Mills Shale	50.0	141.0	92.3
Wise Ridge Coal	89.0	530.0	249.3
Viking B Coal	58.0	328.0	180.8
Upper Block Coal	52.0	222.0	141.8
Lower Block Coal	34.0	204.0	129.7

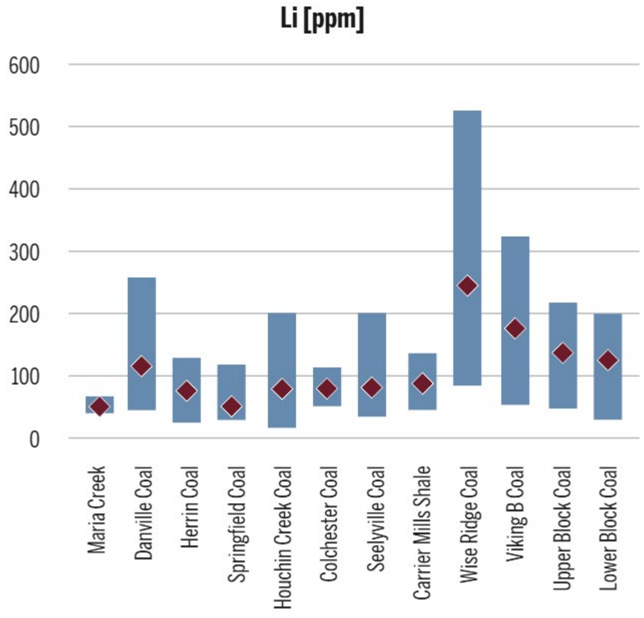


Figure 36. Table data and bar graph of lithium concentrations in the paleosols under the respective coal beds or under shale horizons (from Mastalerz and others, 2022c). Viking B coal is currently formalized as the Montgomery Coal Bed and Carrier Mills shale as the Logan Quarry Shale Member (Mastalerz and others, 2024).

younger coals of the Carbondale Group that often have Li content below 100 ppm.

Various sources report that Li extraction from sedimentary rocks could be viable when Li concentrations are within a wide range of 100 ppm to 20,000 ppm, with the practical threshold depending on many factors. The concentrations documented from the Indiana paleosols (fig. 36) often are within that range, making them a potential target. Because of the wide range of Li content within these paleosols, further examination is warranted to identify stratigraphic horizons containing the highest concentrations. A positive correlation documented between Li and Al_2O_3 suggests that Li is associated with the clay fraction and also indicates that Al can be used for a screening of the paleosols in search of zones with high Li concentrations (Mastalerz and others, 2022c).

2.5.3 Gallium and germanium

Comparison of individual paleosol horizons with regard to Ga content (Table 23) shows that the most Ga-enriched paleosols are those occurring under the Raccoon Creek Group coals (fig. 7). Specifically, the Wise Ridge Coal Bed averages 36.4 ppm of Ga, Montgomery Coal Bed (locally known as Viking B) averages 32.7 ppm, and Upper Block Coal Member averages 29.5 ppm. Compared to the average Ga content of the world coals (5.8 ppm, Ketris and Yudovich, 2009), the paleosols show significant enrichment.

In contrast to Ga, Ge content in paleosols is low, 0.96 ppm on average. Studies on coal have shown that Ge is associated dominantly with the organic fraction (e.g., Dai and others, 2023), and organic-lean paleosols are typically not expected to be a viable source of this element.

In Indiana paleosols, a very strong positive correlation exists between Ga and Al (R^2=0.89, fig. 37) (Mastalerz and Roden, 2023). This correlation informs us that there is a high possibility that if Al content in paleosols exceeds 7 %, Ga will be enriched compared to the Upper Continental Crust (UCC) value of 17 ppm. Gallium concentrations of 34 ppm (twice the UCC value) and higher can be expected when Al content is above 12 %. Having such high coefficients of determination, Al content (routinely measured element in rocks) becomes a great predictor of Ga concentrations. The strong correlation of Ga with Al also suggests that in Indiana paleosols, Ga is associated with clays. In general, a review of the previous studies suggests that Ga can be bound either to mineral components or the organic fraction (Dai and others, 2023), but the association with mineral matter appears to be more common than with the organic fraction.

Table 23. Gallium concentrations in Pennsylvanian paleosols in Indiana.

Paleosol under	Min (ppm)	Max (ppm)	Average (ppm)	Number of samples
Danville	19.3	34.4	29.5	13
Hymera	22.5	32.9	27.7	2
Springfield	10.1	33	20.5	8
Houchin Creek	14.8	33.7	24.5	11
Colchester	24.1	29	26.2	5
Seelyville	18.3	32.4	25.3	9
Wise Ridge	32.5	43.5	36.4	7
Montgomery (Viking B)	30.1	37.9	32.7	4
Upper Block	19.3	37.6	29.5	6
Lower Block	15.8	27.3	22.1	3

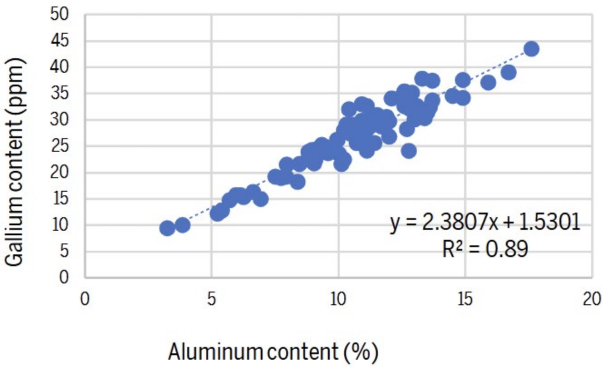


Figure 37. Scatter plot and regression showing correlation between Ga and Al content for paleosol samples from Indiana (from Mastalerz and Roden, 2023).

Industry benchmarks suggest that commercially viable extraction thresholds for Ga are within the 30 to 100 ppm range (Rudnik, 2024), indicating viable extraction potential for many Indiana paleosols. Considering the Chinese standard that takes 30 ppm as the industrial grade of a Ga deposit (Dai and others, 2012), a large proportion of the paleosol samples would meet this requirement (fig. 37), suggesting that Pennsylvanian paleosols should be targeted as a possible source of Ga.

In addition to the concentrations of Ga, the feasibility of technical and economic extraction of this element is the other critical consideration while considering potential sources. Globally, most Ga is produced as a byproduct of processing bauxite and from Zn-processing residues (Sverdrup and others, 2017; USGS, 2022b). Recovery of Ga from U.S. bauxite deposits is unlikely because of their high silica content. Therefore, abundant paleosols could be a good substitute. Similar to bauxite, Indiana paleosols are rich in aluminum (Mastalerz and others, 2022c). The association of Ga with clays in these paleosols could make them suitable for preconcentration and upgrading of the material by physical separation/mineral processing methods.

2.6 Other potential but unexplored sources

2.6.1 Kaolin Group clays

Exploring for REEs in Kaolin Group clays has gained momentum recently as scientists search for analogs to the ion-adsorption clay deposits mined in China for REEs (Sandell-Hay, 2022). Ion-adsorption clays in China, such as kaolinite, are the result of chemical weathering of an igneous parent rock that introduced elevated amounts of REEs (Xie and others, 2016). Although the deposits in China are of lower-grade heavy REE (HREE), light REE (LREE), and yttrium (Y) deposits, these elements can be easily separated from the clays, making them commercially attractive (Xie and others, 2016). In addition to the clays, other minerals are mixed in with the kaolinite deposits, including secondary phosphates and zircon, that may be the source of some REEs (Mentani, 2010; Murakami and Ishihara, 2008).

In the United States, researchers have studied REE concentrations of Paleocene-Eocene kaolin group clays in Georgia (Boxleiter and others, 2024). The REEs present include cerium, terbium, neodymium, and yttrium (Tang, 2023). These clays are thought to have also been derived from the weathering of igneous rocks which were then transported to a marine or marginal marine environment (Munyan, 1938).

Other types of kaolin group clays can occur by the chemical weathering of sedimentary rocks, especially when a conduit exists for water to infiltrate the system such as a fault system or an unconformity surface (Elliot, 2021). Clays that developed from this type of process are present in Indiana. In 1874, Cox proposed the name “indianite” for a white, porcelain-like clay found in Lawrence County, Ind. Ultimately, the name was not formally recognized, and further geochemical studies determined the clay to be a kaolin group clay called endellite (Ross and Kerr, 1935). Callaghan (1948) detailed the clay deposits present at the Gardner Mine Ridge in Lawrence County. In addition to endellite, Callaghan noted the presence of halloysite (dehydrated endellite) and allophane or allophane-evansite. The North Gardner and South Gardner Mines mined aluminum that was used in the production of white porcelain and alum cake until the production stopped in 1891 (Callaghan, 1948; Blatchley, 1896).

The endellite-halloysite clay deposits mined in Lawrence County have also been noted to occur in Owen, Greene, Monroe, Lawrence, Martin, and Orange Counties with reports of possible occurrence in Dubois and Crawford Counties (Callaghan, 1948; Logan, 1922; Logan and Ries, 1922; fig. 38). These clay deposits occur in two settings: at the Pennsylvanian-Mississippian unconformity where sandstones of the Caseyville Formation (formerly Mansfield Formation) are in contact with formations of the Chester Group, or as cavity fillings in sandstones of the Caseyville Formation (Callaghan, 1948). Callaghan (1948, Plates 6 and 7) created detailed cross sections of the mines showing the complex occurrences of endellite relative to the host lithologies.

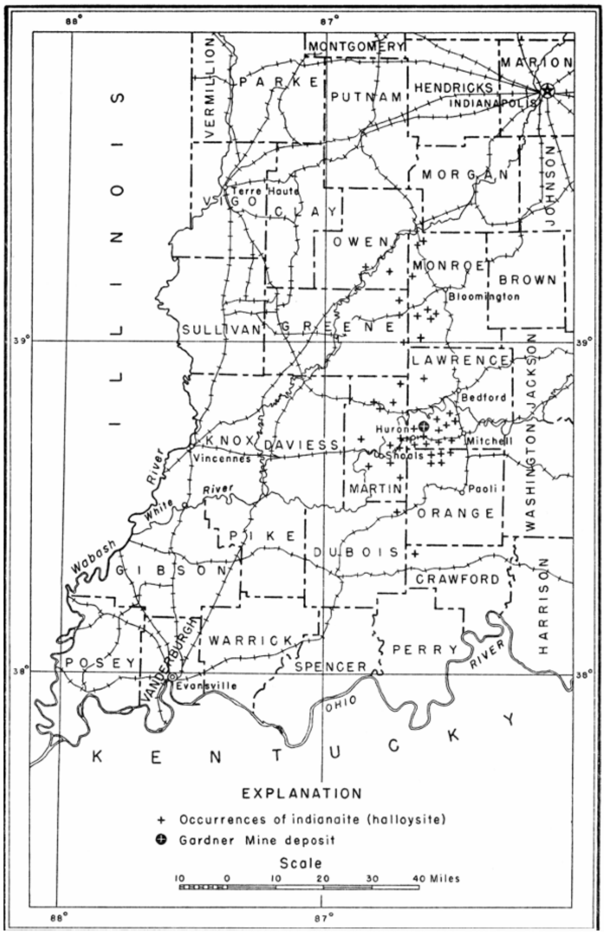


Figure 38. Index map of southwestern Indiana showing distribution of endellite clay or indianite (Logan, 1922).

Based on analogs with other known clay deposits, REE sources have potential to exist either in or associated with the clays; however, REE analysis for the clays present in Indiana are not available. Sampling the elemental composition of the clays in the state will help to better understand if the resource exists.

2.6.2 Produced water

Fluids that return to the surface after an oil and gas well is completed are termed produced water. Part of the well completion process is to stimulate downhole formations with a combination of a fluid (usually water) and an acid. Unconventional sources of oil and gas, like shales, require high volumes of water to be used in the well completion process which is termed high-volume

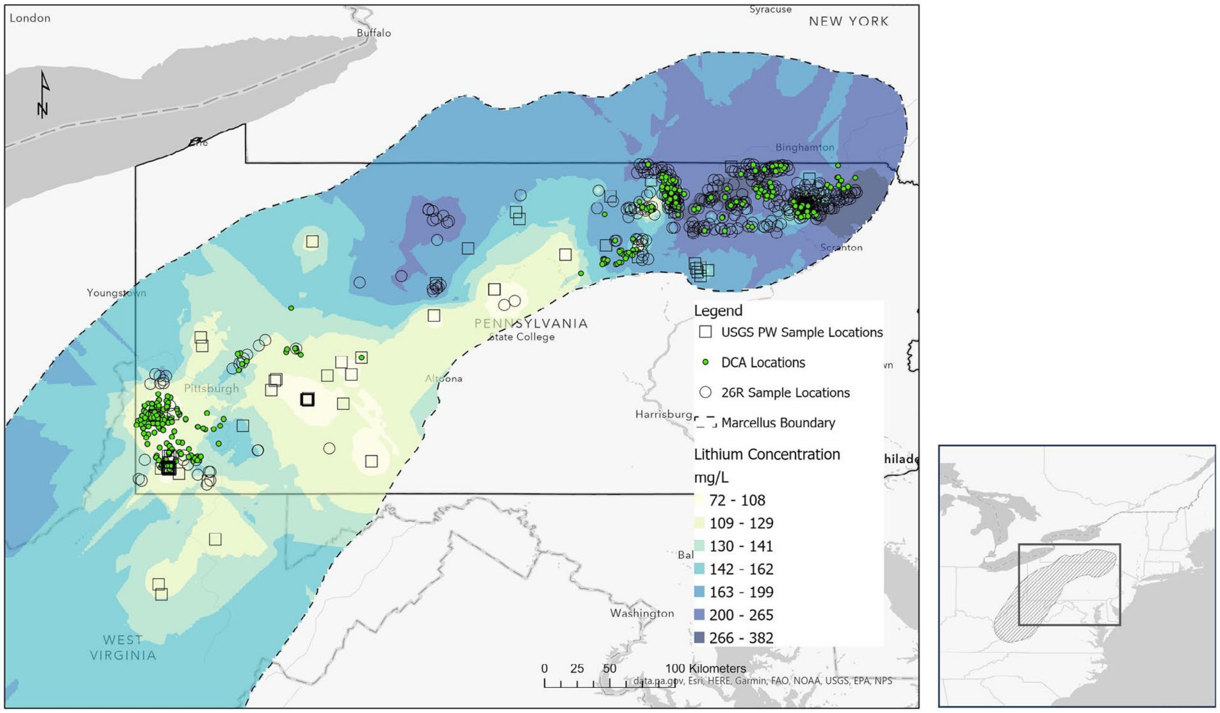


Figure 39. Map of lithium distribution in the Marcellus Shale produced waters (Mackey and others, 2024).

hydraulic fracturing. After completion, the well commonly returns produced water to the surface which is a combination of the water used for the hydraulic fracture stimulation mixed with any fluids that were already present in the formation (termed formation or connate water). Sampling of these produced waters in shale plays like the Marcellus Formation have revealed resources of lithium that were not previously known (fig. 39).

Although the typical well completion stimulation in Indiana uses relatively low volumes of water, those wells can return produced water to the surface after completion. Laboratory analyses of these waters for critical minerals are not publicly available. In addition to oil and gas wells, other wells, such as those drilled for carbon sequestration, may remove formation water in order to create space in the pores for the carbon dioxide to occupy. Ordovician and Cambrian formations that are targeted for carbon sequestration in Indiana have acted, throughout geologic time, as conduits for mineralized brines that are associated with the Mississippi Valley-Type (MVT) deposits found in adjacent states (Gregg and Shelton, 2012). Although no economic MVT deposits have been found in Indiana, residual critical minerals may exist in the formation water that could be of importance (Shaffer, 1981). Historic data from Indiana's mineral springs and wells, derived from formation water, that were popular in the early 1900s (Blatchley, 1901) have limited analyses for the critical mineral lithium, but sufficient evidence exists to suggest that this is an area that can and should be further researched.

3. CURRENT REE-CM EXTRACTION METHODS

Recovering rare earths and critical minerals is a step-by-step process. It starts with physical beneficiation—methods like density separation, magnetic separation, and froth flotation. These techniques might trim costs and prepare feedstock but only modestly boost element concentrations (Table 24). The heavy lifting comes with metallurgical pre-treatment. Pyrometallurgy, often paired with acid leaching, converts stubborn minerals into soluble oxides, making extraction easier. Hydrometallurgy with common acids is a standard approach; solvometallurgy using ionic liquids is an experimental but promising alternative. Finally, metals must be separated and purified. Solvent extraction dominates but struggles with impurities. Ion exchange and crystallization play niche roles, while new ideas—chromatography, membranes, even engineered microbes—are moving from lab to pilot scale. Together, they show promise in making coal ash, tailings, and other materials into viable sources of critical minerals.

3.1 Physical beneficiation for preliminary REE-CM enrichment

Physical beneficiation of the original feedstock is an initial step toward element extraction. Pre-concentration of REEs and other elements relies on the premise that there is some partitioning of elements between different fractions of the material and by removing some fractions, the remaining material will be enriched in those elements. In addition to pre-concentrating elements, physical beneficiation also provides other advantages, including a) producing more uniform feed for subsequent chemical processing; b) eliminating oversized material; and c) eliminating carbon and magnetics that usually have low REE content.

Density separation, magnetic separation, and froth flotation are the most common techniques of physical beneficiation. *Density separation* is based on the principle that different minerals have different densities. For REEs, density separation alone, however, is rather ineffective (Thomas and others, 2024). *Magnetic separation* is based on the isolation of minerals with magnetic properties, and could be more effective depending on the element association. If REEs occur in paramagnetic monazite [(Ce,La, Nd, Th) PO_4] crystals, pre-concentration might be effective. On the other hand, if REEs occur in other phases, they are usually non-magnetic and could concentrate in the non-magnetic fraction. *Froth flotation* is based on the principle of surface hydrophobicity and uses chemical reagents that can separate out REE-bearing minerals. The effectiveness of this technique depends on the selection of chemicals, particle diameter of the material (optimal is 40–100 micrometers, and pH (best is 7.5–11.5).

Table 24 lists standard preconcentration methods used on coal fly ash in various countries, including sieving, flotation, and magnetic separation. These examples show low enrichment ratios of these techniques, and the need for developing more effective techniques. However, considering its multiple benefits, physical beneficiation is rather desirable because it reduces overall costs of the subsequent extractions.

Table 24. Examples of physical beneficiation results from coal fly ash (from Fu and others, 2022).

Location	Recovery method	Original REE content	Enrichment ratio
China	Sieving	550	1.98
UK	Sieving	570	1.19
UK	Flotation-magnetic separation-size classification	637	1.26
USA	Sieving	593	1.16
USA	Density fractionation	522	1.02
USA	Magnetic separation	666	1.06
USA	Froth flotation	920	1.46
USA	Magnetic separation-sieving	366	1.13
Poland	Sieving	271	1.17
Indonesia	Sieving	249	1.1
Indonesia	Magnetic separation	278	1.12

3.2 Metallurgical pre-treatment: hydrometallurgy, pyrometallurgy, and solvometallurgy

While REEs could be slightly enriched as a result of physical beneficiation, typically, further pre-treatment is needed to generate higher-grade concentrates, and metallurgical pre-treatment is often chosen as the next stage. The main purpose of metallurgical pre-treatment is to convert difficult-to-leach phases in the targeted materials to more easily leachable fractions. Three types of metallurgical pre-treatment are used: hydrometallurgy (use of aqueous chemistry), pyrometallurgy (reactions at high temperature), and solvometallurgy (use of non-aqueous chemistry). Choosing a technique for metallurgical pre-treatment requires a good understanding of element association and leaching science of the element-bearing minerals.

3.2.1 Pyrometallurgical pre-treatment

Pyrometallurgy involves processes that use heat with or without chemical reagents to mobilize metals and prepare them to be extracted and converted to high-purity oxides. This technique includes: calcining—thermal decomposition of the metal in the absence of oxygen; roasting—using heat and oxygen; and smelting and refining—both involving thermal reaction with molten phases. Such pre-treatment is typically carried out at temperatures between 200 and 500°C in an acid-resistant, brick-lined furnace.

In the REE production industry, pre-treatment through pyrometallurgy is commonly used. Calcination of monazite, bastnasite, and xenotime (minerals found in coal ash) with sodium carbonate, sulfuric acid, ammonium chloride, sodium hydroxide, or other agents at high temperatures have been used to convert difficult-to-leach minerals to easily leachable forms. The particular objective is to produce the oxide form of REE (RE_2O_3); the oxide form RE_2O_3 is acid-soluble and the subsequent acid leaching could effectively remove the metal from the hosting matrix. This is especially important for coal ash material where REEs are hosted by glassy aluminum-silicate phases that are very difficult to leach.

Pyrometallurgical treatment with conjunction with hydrometallurgy has been experimentally shown to increase REE recovery from coal ash. Acid leaching is the most common type of REE leaching. The common acids used in leaching from primary sources are sulfuric acid (H_2SO_4), hydrochloric acid (HCl), nitric acid (HNO_3) or their compounds (Peiravi and others, 2021). Extensive studies have been done on leaching REEs from coal ash and coal refuse (Zhang and Honaker, 2020 a, b). For coal ash, composed dominantly of aluminosilicate glass, leaching with HCl alone does not completely dissolve REEs because they are encapsulated in the difficult-to-dissolve matrix. Therefore, subsequent leaching with NaOH and HCl is required to facilitate the dissolution of REEs.

3.2.2 Solvometallurgical pre-treatment

Solvometallurgy involves the extraction of metals from the parent materials utilizing non-aqueous solutions, specifically ionic liquids (IL) and deep eutectic solvents (DES).

IL and DES have emerged as a new class of green solvents for REE extraction and separation. IL are solvents composed of a discrete cation and anion, whereas DES are a mixture of diverse ions. Although numerous studies have been conducted on the use of IL and DES, the mechanisms of leaching during REE recovery are not yet well understood and thus their application is presently limited. Better understanding of selectivity of metal dissolution using IL and DES is needed to increase leaching efficiency during sequential leaching processes of coal and coal ash.

3.3 Separation and purification of REEs from leachate

Once the metals have been leached, they need to be extracted from their leachate solutions. The three most common separation methods include: a) solvent extraction; b) ion exchanges, and c) selective crystallization (precipitation).

In selective crystallization, precipitating agents include sulfate, carbonate, fluoride, phosphate, and oxalate. This method relies on the water solubility of REE-sodium double salt, which increases from La to Lu. However, the difference in solubility is small and therefore, the process has proven to be rather inefficient.

Ionic exchange is a separation method where leachate is pumped through a sulfonic resin-filled ion exchange column. There, REEs are abstracted onto sulfonic resin beads and subsequently removed from the column by eluting them with complexing agents such as EDTA or amino-polyacetic acid complexant (HEDTA, DCTA, TTHA). The complexed REEs are further precipitated with precipitating agents. This technique, however, because of its disadvantages (low yields and environmental difficulties with toxic solution), is not used anymore for REE separation, having been replaced with solvent separation (SX) methods.

Solvent extraction (SX) uses organic liquid that has affinity to the target ions, mixed with the leaching solution to absorb the target ions. This extraction system relies on the relative ability of solutes to distribute between aqueous and organic phases. The organic extractant contains molecules that bond with the desired ions to form organic metal complexed with a high solubility in the organic phase and low solubility in the water. The main extractants used in solvent extraction of REEs are phosphatic organic compounds: di(2ethylhexyl), prosphoric acid (DEHPA), tributyl phosphate (TBP), tetraoctyl diglycol amide (TODGA), CYANEX272 (dialkyl phosphinic acid) and CYANEX923 (liquid phosphine oxide). The presence of impurities such as ferric iron (Fe3+) and aluminum poses a challenge for solvent extraction of REEs. The ions have close ionic radii and charge densities of that of REE cations, and thus end up in the extractant. To resolve the inefficiencies of currently used methods of solvent extraction, new techniques such as novel chelants, modified SX processes, and chromatography have been introduced.

3.4 Other less common, innovative techniques

Electrochemical REE recovery has been investigated in some studies, including in coal and fly ash. Some studies utilized this method starting from REE solubilization (REEs are mobilized from their solid matrix to the analyte), followed by the dissolution of the ionic form of REEs mobilizing toward the polarizing electrodes, and the reduction of REEs at the cathode. The advantage of this technique is avoiding the massive use of toxic chemicals.

Membrane separation techniques utilize well-known filtration processes such as nanofiltration (NF), reverse osmosis (RO), emulsification liquid membrane (ELM), and hollow fiber liquid membranes (HFLM). Studies utilizing these techniques have shown that they can effectively concentrate REE mixtures for the leachate solutions. Only few studies were able to produce individual metals.

In microbial and biochemical extraction, bioengineered microorganisms for the adsorption of REEs are used to extract REEs from solution. Studies on REE from acid leachates (Park and others, 2017) utilizing genetically modified strains of E.coli bacteria for a high-density cell surface display lanthanide binding tags (LBTs) on their S-layer OmpA proteins concluded that by engineering the native bacteria surface, REE biosorption of high efficiency (higher for HREEs than for LREEs) and selectivity can be achieved from low-grade feedstocks. Several other laboratory studies have also shown a promise in aiding the recovery of critical minerals using microbial and biochemical extractions.

Chromatography-based separation has recently gained attention due to its potential for industrial extraction of critical minerals. Particularly, the emergence of solvent-impregnated resin (SIR) and supported ionic liquid (SIL) techniques have attracted attention. In both approaches, the most effective extractant is selected and the material is impregnated with it. The solvent, permeating into the material, facilitates the extraction. Solvent extractants such as N,N-dimethylformamide (DMF), TODGA, and Cyanex923 are commonly impregnated onto silica and resin. In comparison to liquid-liquid extraction (LLE), solid-liquid extraction (SLE) systems that utilize various types of resins may be a more environmentally favorable approach.

Extraction and separation based on ligand-assisted displacement (LAD) chromatography deserves special attention because it was developed by the Purdue University team, is environmentally friendly, and is relatively cost effective. This patented technique is used by ReElement Technologies LLC located in Fishers, Ind. (https://www.reelementtech.com/)

4. RECOVERY OF REE-CM FROM LOW-GRADE FEEDSTOCK AND EXTRACTION FEASIBILITY ASSESSMENT

Indiana hosts a large potential supply of REEs hidden in coal refuse, coal ash, and other low-grade feedstocks. Numerous studies, laboratory experiments, and pilot projects show that coal refuse holds REEs mostly in mineral fractions, but simple separation methods barely move the needle. Chemical leaching—especially when paired with alkali or thermal pretreatment—could deliver recoveries of 80–90 % (Table 25). Even so, costs remain high, which means attention should center on the largest deposits, like the Springfield Coal waste in several Indiana counties (figs. 10–13).

Coal ash may be the biggest prize. Indiana produces more than 5 million tons a year, and some recovery tests on coal ash worldwide top 90 % when roasting with NaOH precedes acid leaching (Table 26). Finer fractions tend to be richer in REEs, making targeted beneficiation worthwhile. By one estimate, Indiana's ash impoundments contain more than $5.8 billion in REEs (Table 32). Acid mine drainage adds another angle: staged precipitation can concentrate REEs to more than 1,000 ppm, and pilot plants in the U.S. have produced high-purity oxide products above 80 %. Because the state regulations already require AMD treatment, recovery could help offset mandated remediation costs.

Gallium could tip the scales for Indiana's paleosols. Though REE levels in paleosols are modest (208 to 343 ppm, fig. 32), gallium concentrations often exceed industrial thresholds (Section 2.5.3; fig. 37), making combined Ga-REE recovery a promising path. Shales bring vanadium, zinc, and other metals into play, though more data are needed. Taken together, Indiana's unconventional feedstocks show technical feasibility, but economics will depend on slashing processing costs, co-producing byproducts, and aligning with federal and state efforts to reduce reliance on Chinese supply chains.

In this chapter, recovery methods from low-grade feedstock are discussed based on published data generated in laboratory settings or pilot-scale projects. The emphasis is on the materials available in Indiana: coal and coal refuse (4.1); coal combustion ash (4.2); acid mine drainage (4.3); paleosols (4.4), and metalliferous shales (4.5).

Table 25. Selected results of salt and acid leaching of REEs from coal and coal refuse (Zhang and others, 2020b).

Material	Coal	Extraction conditions	Leaching recovery
Lignite	Fort Union	0.5M H_2SO_4, 40°C, 48h	Nearly 90 % of total REEs
Decarbonized middlings	Fire Clay	Nitric acid solution of pH 0 at 75°C	83 % of total REEs, 86 % of LREEs and 69 % of HREEs
Decarbonized middlings	W Kentucky #13	Nitric acid solution of pH 0 at 75°C	15 % of La, 21 % of Ce, 31 % of Nd, 45 % of Y
Decarbonized middlings	Lower Kittanning	Nitric acid solution of pH 0 at 75°C	41 % of total REEs
Decarbonized slurry	Fire Clay	Nitric acid solution of pH 0 at 75°C	31 % of La, 26 % of Ce, 40 % of Nd, 36 % of Y
Decarbonized slurry	W Kentucky #13	Nitric acid solution of pH 0 at 75°C	6 % of La, 5 % of Ce, 16 % of Nd, 34 % of Y
Decarbonized slurry	Lower Kittanning	Nitric acid solution of pH 0 at 75°C	2 % of La, 5 % of Ce, 8 % of Nd, 25 % of Y

4.1 REE recovery from coal and coal refuse

REEs in coal preparation plant refuse have modes of occurrence similar to the original coal and these have been widely reviewed by coal geologists (Dai and Finkelman, 2018; Dai et al., 2023). Compared to the coal, coal refuse has a lower contribution of the organic fraction (but still high organic content) and a more abundant mineral fraction. Consequently, elements associated with the inorganic fraction in coal will be concentrated in coal refuse (gob piles, tailings) compared to the original coal. Below we outline the steps of recovery of REEs from coal refuse.

1. Physical beneficiation (separation by gravity, magnetic, or flotation). Often prior to physical beneficiation, decarbonization of the material is performed to produce clean coal. Gravity-based separations are used for relatively coarse material, but in general, they are not very effective for coal refuse, yielding an enrichment factor not higher than 1.2 (Zhang and others, 2020a). Froth flotation is typically used for finer-grained refuse, utilizing varying degrees of surface hydrophobicity, and

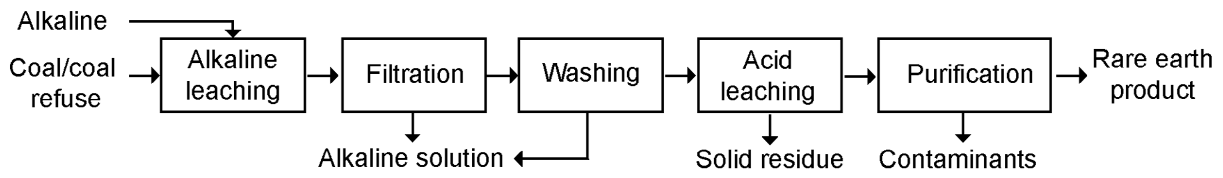


Figure 40. Schematic diagram of the alkaline-acid leaching process to extract REE from coal and coal refuse (Kuppusamy and others, 2019).

it can be more effective than the gravity-based methods. An alternative to flotation, the hydrophobic-hydrophylic separation (HHS) process, is a novel technique that provides improved recovery of micro-size material while also providing a dewatered product. Magnetic separation can also be somewhat effective if differences in magnetic properties exist between REE minerals and the matrix. Overall, however, there is a consensus that the recovery values from all these physical beneficiation techniques are generally too low to make them economically viable. Practically, the gains from these operations need to be compared to the energy cost of the physical beneficiation to make a decision about the value of this technique.

2. Chemical extraction. Because of the low recovery and high cost of physical beneficiation, direct chemical extraction of REEs has been used for coal sources (Yang and others, 2018). Chemical extraction could be accomplished by a) salt and acid leaching, and b) alkali and thermal pretreatment (fig. 40). In salt and acid leaching, ammonium sulfate is commonly used as a salt lixiviant; results vary with regard to the effectiveness of REE extraction. REEs could be effectively extracted by using acid solutions. For example, 0.5 M H_2SO_4 was used to extract nearly 90 % of total REEs from lignite (Laudal and others, 2018), owing to the fact that REEs are organically bound in low-rank coals. For bituminous coal and coal refuse (like those in Indiana), the results of acid leaching were not very satisfactory; recovery of REE was relatively low (<30 %) (Honaker and others, 2017). Overall, while direct salt and acid leaching is a promising choice for low-rank coal and its refuse, for higher-rank coal and coal refuse, it failed to provide satisfactory recovery in the majority of cases. Examples of salt and acid leaching results are presented in Table 25.

Alkali and thermal pretreatments were used to enhance leaching recoveries (fig. 40). The 8 M NaOH is often used to treat decarbonized refuse prior to acid leaching. In addition, thermal activation (calcination or roasting) is also used to enhance REE leachability. For example, calcination at 600°C for 2 hours followed by 1.2 M HCl at 75°C for 5 hours yielded recoveries of 81 % total REEs (89 % LREE and 27 % HREE) on coarse refuse, and 28–76 % of total REE on fine-grained refuse (Zhang and Honaker, 2019).

Chemical extraction, although able to recover REEs from coal and coal refuse, also has negative aspects that need to be resolved to make the whole process economically viable. For example, alkali leaching results in contaminants dissolved into solution together with the REEs, which complicates the purification process. In addition, the chemical cost of both alkali and acid solutions, as compared to the value of recovered REEs for this low-grade coal-based feedstock, may be economically prohibitive.

Considerations for recovery of REE-CM from Indiana coal refuse

1. The largest coal refuse deposits should be given priority in terms of site selection for their further evaluation and potential recovery. Some large sites like those of the Springfield Coal waste in Warrick County (fig. 13) could be targeted. In addition, smaller sites with the refuse from the Tradewater Formation coals that often have elevated REE concentrations should be considered.
2. Efforts should be put toward the effectiveness of physical beneficiation to pre-concentrate critical materials. For fine-grained refuse (coal tailings and slurry), density separation would help to decarbonize the material. Coal tailings and slurry deposits in Indiana have carbon content in the range of 20 to 50 %, and with REEs being dominantly associated with the mineral fraction, removing the carbon would result in the REE pre-concentration in the heavier fraction. Finding a beneficial use for the carbon fraction could also lower the cost of recovery. For coarse-grained material (gob piles), crushing and subsequent size separation could be somewhat beneficial. However, the gains from physical beneficiation need to be compared to the energy cost of such operations to make a decision about the value of this technique.
3. Leaching of the physically pre-concentrated material (both coal tailings, slurry and gobs) should include alkali/water/acid leaching stages. Alkaline

leaching with NaOH is often used on decarbonized material prior to acid leaching. To enhance leachability, thermal activation (e.g., calcination or roasting at 600°C) followed by acid (e.g., HCl, HNO_3) leaching (at 75°C) would be more effective than acid leaching alone. Chemical extraction, although able to recover REEs from coal and coal refuse, also has negative aspects that need to be resolved to make the whole process economically viable. For example, alkali leaching results in contaminants dissolved into solution together with the REEs, which complicates the later purification process. In addition, to treat large quantities of the waste material, large quantities of chemicals are needed, resulting in large costs of the operation.

4.2 REE recovery from coal combustion byproducts

Coal fly ash is composed of an amorphous phase (60–90 %) and crystalline phases. Crystalline phases include quartz, mullite, hematite, magnetite, spinel, and other minerals. The amorphous glassy phase is composed of difficult-to-leach aluminosilicates. Numerous studies demonstrated that REEs are dominantly dispersed in the glassy phases or Al-Si-oxide phases (Pan and others, 2019) and that the heterogeneity of REEs occurs in nano- and atomic-scales (Hower and others, 2019). Many REE-bearing minerals such as monazite, xenotime, rhabdophane, zircon, ilmenite, and calcite have been found in fly ash, but their associations with the major phases are complex. All this makes it very difficult to obtain good recovery of REEs from fly ash. A schematic process of the REE recovery from coal to pure REEs is shown in figure 41.

The process of REE recovery from coal ash involves the following steps:

1. Physical beneficiation (density separation, particle size separation, magnetic separation, or froth flotation). The effectiveness of physical beneficiation depends on a good understanding of REE-bearing minerals and their association. Density separation could be somewhat effective if REEs are hosted by heavier minerals, such as bastnasite, xenotime, and monazite (density range 3.9–5.5 g/cm^3). Magnetic separation could separate REEs hosted by magnetic minerals (e.g. monazite) from those associated with non-magnetic fractions. Several studies suggested that coal fly ash contains a concentration of REEs in the fine fraction (for example, 500-mesh, 25 micrometers)

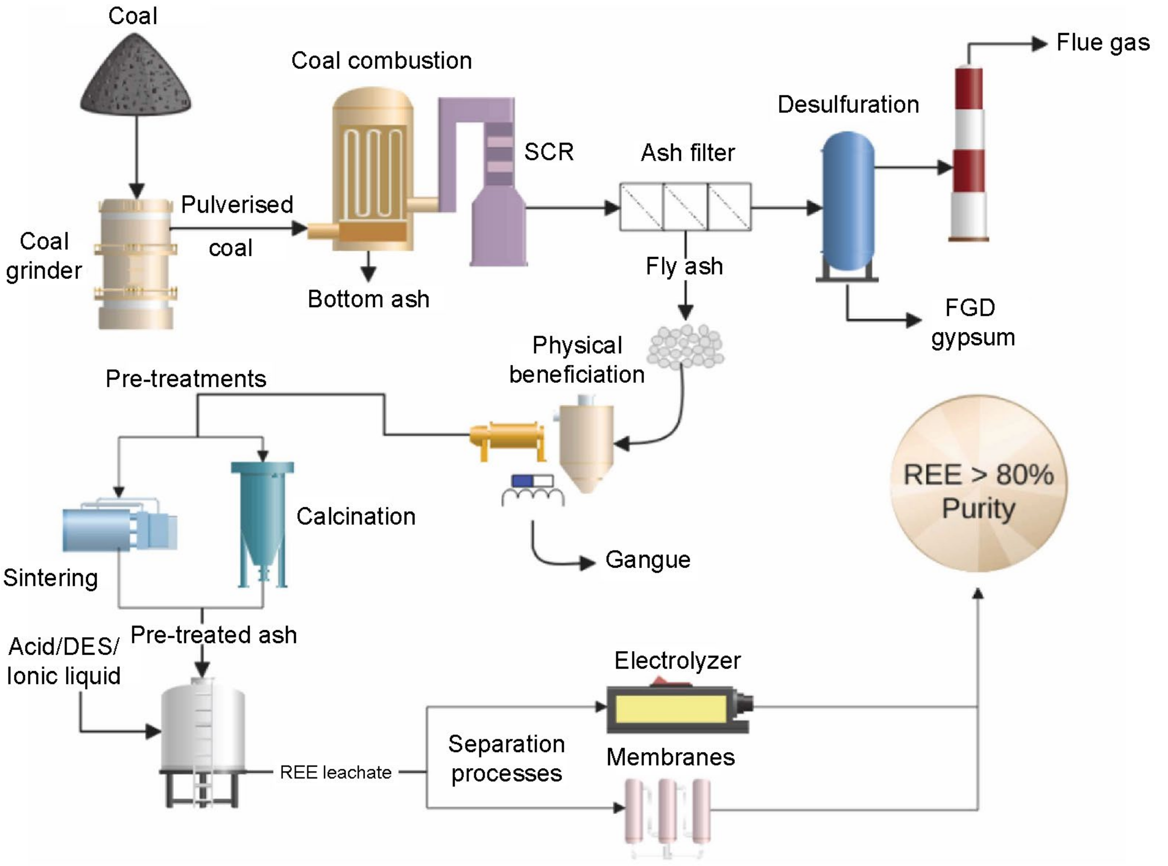


Figure 41. General schematic showing the steps in REE extraction and separation (from Thomas and others, 2024).

compared to coarser fractions. In essence, physical separation of fly ash can provide a higher-grade material for the downstream extraction processes, resulting in a reduction in the overall recovery cost. However, the selection of physical pre-concentration strategy for a specific fly ash should be based on a comprehensive laboratory evaluation of REE partitioning characteristics (Zhang and others, 2020b).

2. Chemical and/or thermal pre-treatment before acid leaching is typically required to achieve higher REE recovery. Pre-treatment, pyrometallurgical or in conjunction with acid reagents (hydrometallurgy), is used to dissolve/transform the REE hosting material and liberate metals to produce "pregnant leach solution." Calcination, roasting, and sintering are examples of processes in this phase. For example, Taggart and others (2018) compared performance of various roasting additives including Na_2O_2, NaOH, CaO, Na_2CO_3, $CaSO_4$, and $(NH_4)2SO_4$ by performing roasting tests at 450°C on various fly ash samples from power plants in the Appalachian, Illinois, and Powder River Basin, followed by leaching with 1 M HNO_3. It was found that NAOH roasting often recovered more than 90 % of the total REEs, performing better that the other additives.
3. Acid leaching has been proven to be relatively effective for some coal ash. For example, 70 % of the total REEs were extracted from the fly ash of the Powder River Basin coal using 15 M HNO_3 at 85–90°C (Taggart and others, 2016). Almost 100 % recovery was obtained using 12 M HCl at 85°C, and 71 % of REEs was extracted with much weaker (1 M) HCl. However, using acid leaching alone, REE recovery is often lower. Specifically, 35–43 % and 40–57 % of total REEs were extracted from fly ash of the Illinois and Appalachian basins, respectively, using strong acid (12 M HCl) at 85°C (King and others, 2018).

In addition to HNO_3 and HCl, H_2SO_4 was also used to extract REEs from fly ash. Among these three acids, so far HCl has been most commonly used. Sulfuric acid is expected to be least effective because calcium present in the ash will complex with sulfate to form gypsum, and some REEs will be incorporated into the gypsum structure and will be lost to the precipitate. In general, leaching recovery is sensitive to liquid-to-solid ratio, acid concentration, temperature, and leaching duration. Leaching recovery of La, Ce, and Nd from fly ash almost doubled when increasing the liquid-to-solid ratio from 5/1 to 20/1 or extending the reaction time from 30 to 180 minutes (Cao and others, 2018). Figure 42 shows two flow diagrams of REE recovery from coal ash using acid leaching. In case A (Kumari and others, 2019), tris-2-ethylhexyl amine (TEHA) was used to complex hydrogen ions during the solvent extraction step, and subsequently acid was regenerated in the stripping step, which reduced the cost of chemicals. REEs were recovered from the raffinate of solvent extraction using precipitation. In the case B, the ash was leached using diluted acid (e.g., 1.2 M HCl) (Kumari and others, 2019). REEs in the pregnant leach solution were extracted using a three-stage counter-current solvent extraction (SX) system. Subsequently, a concentrated solution of REEs was produced from the SX-stripping stage. High-purity REE concentrates were produced by selective precipitation using oxalic acid as the precipitant. Overall, so far REE recovery from coal ash using direct acid leaching is rather inefficient (Honaker and others, 2019). Harsh leaching conditions with a concentrated acid solution at relatively high temperature are required to achieve satisfactory recovery.

Examples of published studies with higher REE recovery and methods used to recover them are listed in Table 26 and shown in fig. 42. Figure 43 is a diagram showing techniques that have been used for coal ash in various published studies and is a suggested roadmap to consider for REE recovery.

Considerations for recovery of REE-CM from Indiana coal ash

1. The largest coal ash deposits should be given priority in terms of site selection. Therefore, the coal ash impoundments of Duke Energy (Gibson, Cayuga, Gallagher, and Wabash, fig. 19) could be the initial target, and the roadmap presented in figure 43 could be a guide for initial consideration of recovery process.
2. Physical beneficiation of Indiana coal ash could provide a higher-grade material for the downstream extraction processes, resulting in a reduction in the overall recovery cost. However, the selection of a physical pre-concentration strategy for a specific fly ash should be based on a comprehensive laboratory evaluation of REE partitioning characteristics. Publicly available data on REEs in Indiana ash are sparse, and these partitioning characteristics are not well understood. Perhaps confidential data are available from Indiana power plants, and it would be very beneficial to acquire such data. Based on the coal ash data from other coals of bituminous rank, density separation and size separation could be effective for the Indiana ash to preconcentrate REEs.
3. Chemical and/or thermal pre-treatment would be required before acid leaching. For example, roasting (450°C) with some additives (e.g., NaOH), followed by leaching with HNO_3, has been shown to obtain good REE recovery from coal ash, including that from the Illinois Basin.

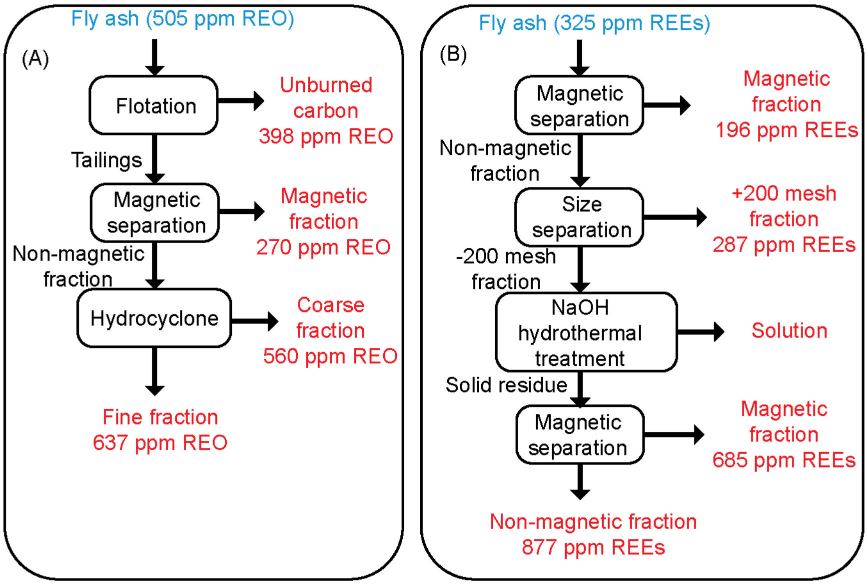


Figure 42. Flowsheets showing the process of preconcentration of REEs from coal ash (Zhang and others, 2020a).

4. Acid leaching is the main stage during the coal ash processing. Strong HCl, HNO_3, and H_2SO_4 could be used for Indiana coal ash, perhaps prioritizing HCl. Leaching recovery is sensitive to liquid-to-solid ratio, acid concentration, temperature, and leaching duration, and these should be carefully designed. In general, because REEs in coal ash are concentrated in difficult-to-leach glassy aluminosilicates, harsh leaching conditions with concentrated acid solution at relatively high temperature will likely be required to achieve satisfactory recovery, consequently resulting in a high cost for the project. Utilization of post-REE extraction residual ash (e.g., in cement industry) could offset the cost of extraction.

4.3 REE recovery from acid mine drainage

Many studies have been performed to recover valuable components such as Fe, Al, Cu, Zn, Ni, and sulfuric acid from acid mine drainage (AMD). The recovery methods involve precipitation, adsorption, diffusion dialysis, and ion-exchange (Zhang and others, 2020a). Due to the much higher economic values of REEs compared to major metals such as iron and aluminum present in AMD, REE recovery from AMD has received significant attention. In one of the prior studies (Zhang and Honaker, 2018), staged precipitation tests were performed on a coal mine drainage site (6.14 ppm of REEs) and the result was an REE pre-concentrate containing 1.1 % of REEs with a pH range of 4.85–6.11. In addition to REEs, the pre-concentrate also contained 17.1 % Al, 1.7 % Zn, 1.4 % Cu, 1.14 % Mn, 0.5 % Ni, and 0.2 % Co, indicating that multiple valuable components can be pre-concentrated simultaneously using staged precipitation. By using selective re-dissolution and oxalic precipitation, a product containing 94 % rare earth oxides was finally obtained from the pre-concentrate. In another study, Ramasamy and others (2018) synthesized N- and O-ligand-doped mesoporous silica-chitosan hybrid beads for extracting REEs from

Table 26. Examples of published studies with high recoveries of REEs from coal ash.

Material	Method	Performance	Source
Fly ash, USA	Reacting with 6.25 mol/L NaOH at 85°C, flowed by acid leaching with 20 % HCl	Up to 85 % recovery of REE+Y	(King and others, 2018)
Fly ash, USA	Reacting with 5 ml/L NaOH at 100°C	REE+Y was enriched from 325 to 877 ppm	(Lin and others, 2018)
Fly ash, USA	Roasting with Na_2O_3 at 850°C, followed by sequential leaching with ware and 6 mol/L HCL	>90 % recovery of REE+Y	(Pan and others, 2021)
Fly ash, China	Reacting with 40 % NaOH solution at 150°C followed by acid leaching with 8 mol/L HCl	88.15 % of REE+Y recovery	(Wang and others, 2019)
Fly ash, China	Reacting with 3 mol/L NaOH at 80°C followed by acid leaching with 3 mol/L HCl	95.5 % recovery of REE+Y	(Wen and others, 2020)

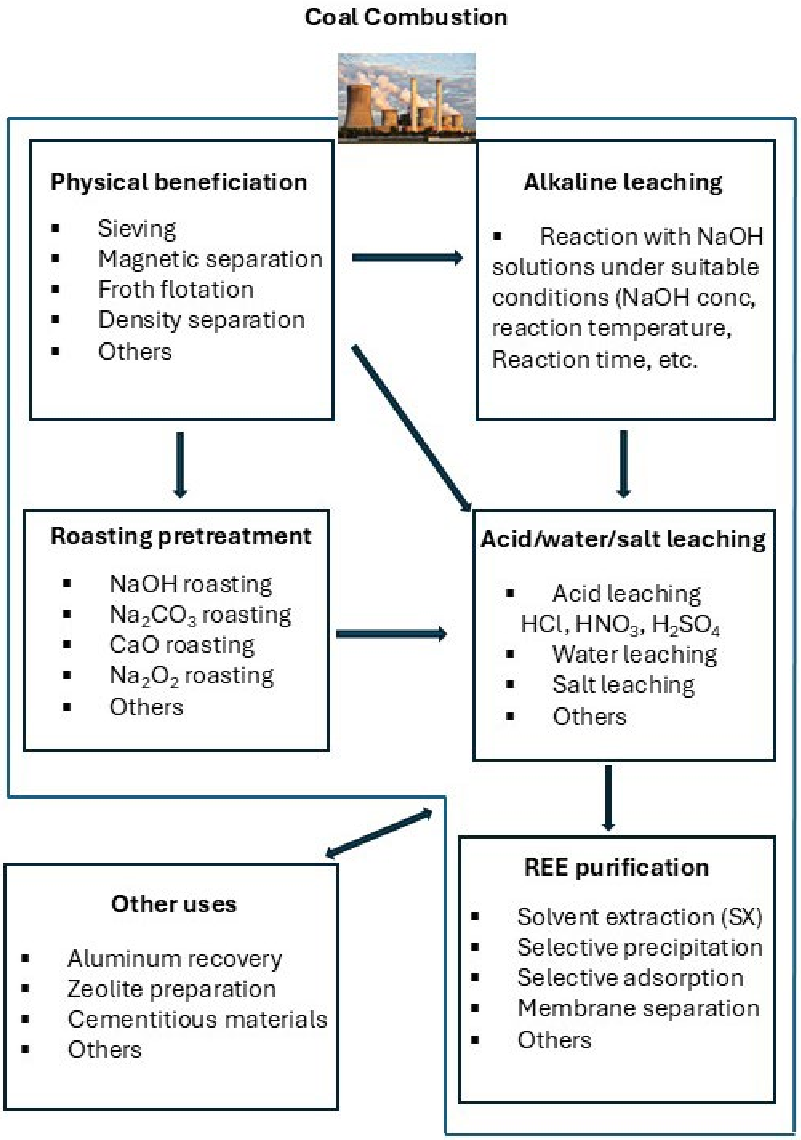


Figure 43. Roadmap for REEs recovery from coal ash based on findings from various published studies.

AMD and the test results showed that more than 90 % of REEs were recovered (Ramasamy and others, 2018).

A study by Vass and others (2019) shows that REEs in AMD treatment sludge can be economically recovered by solubilization followed by REE extraction from the solution. Further work by the same group has led to the design and construction of an acid leaching/solvent extraction mini-pilot plant for the recovery of REEs from AMD sludge. Leaching data showed that high recoveries of REEs (>80 %) could be achieved at a pH value of 1.0 using sulfuric acid. Moreover, the addition of a leaching modifier increased the leaching recovery from 65 % to >95 % at a pH of 2.0. Together with the downstream solvent extraction operation, the continuous pilot process was able to produce high-grade mixed rare earth oxide products exceeding 80 % purity. Techno-economic analysis showed favorable economic outcomes; however, the authors noted that the results were very sensitive to consumable costs (Ziemkiewicz, 2019; Ziemkiewicz and Noble, 2019).

Based on the various results, a flowsheet for REE recovery and comprehensive utilization of AMD was proposed (Zhang and others, 2020a) (fig. 44). Zhang and others (2020a) state that the cost for the staged precipitation step is minimal given the fact that treatment of AMD is mandated by regulatory agencies. In addition, since only a small quantity of REE-enriched precipitate is obtained from the staged precipitation step, chemical consumptions associated with the downstream processes are low. Overall, AMD can be considered to be a promising source of REEs.

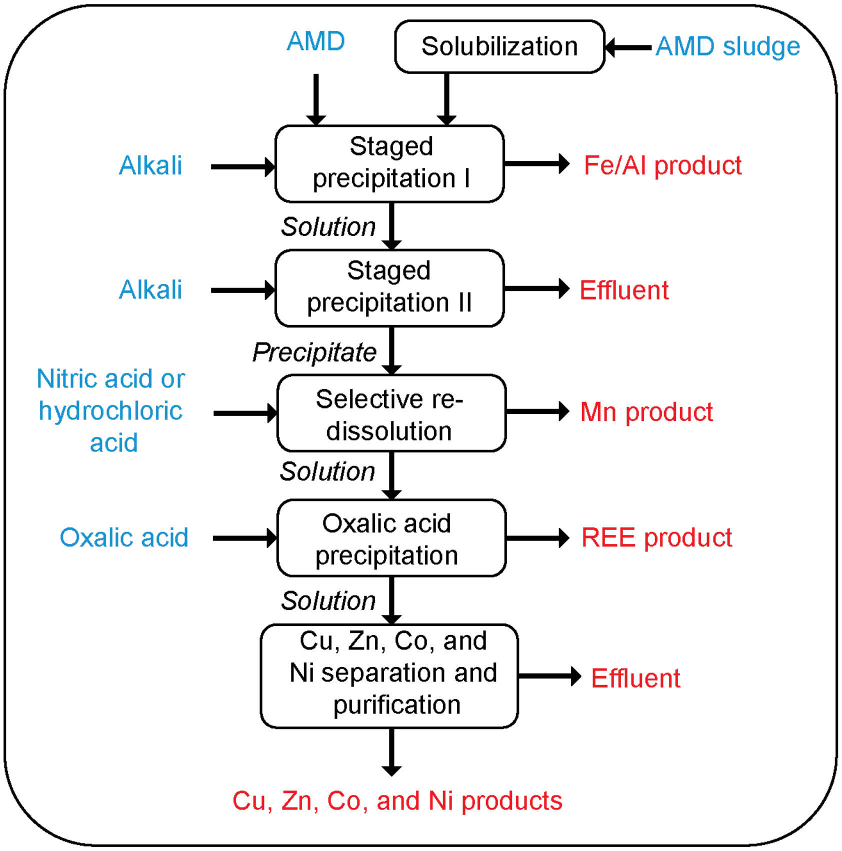


Figure 44. A flowsheet for multiple metal recovery from AMD and acid mine drainage sludge (Zhang and others, 2020a).

A recently developed alternative is in-situ extraction of REEs from AMD (U.S. pat. No. 11,230,75381). This promising technology allows for the direct extraction of REEs from AMD, while at the same time removing excessive mineralization from the seep, including toxic elements such as arsenic, allowing the effluent to meet NPDES (National Pollution Discharge Elimination System) standards. Commercial operations using this technology have been receiving grants to demonstrate their ability to not only extract REEs, but also to improve the water quality of AMD seeps.

Considerations for recovery of REE-CM from Indiana AMD

The benefits of REE-CM extraction from AMD are both economic and environmental. The economic side is the recovery of critical minerals, led by the recovery of REEs, but also other elements. Environmental benefits are primarily in the removal of both desired critical minerals as well as excess mineralization that degrades the quality of streams. Field methods capable of improving discharge water to meet NPDES standards are very beneficial to surface water quality.

The major hindrances to being able to deploy the critical mineral recovery field methods at abandoned mine sites include a lack of access roads and a power supply to run the equipment. Several AMD sites in Indiana are remotely located, with poorly maintained access roads, many of which are now no more than overgrown paths. Similarly, there are very few sites with access to nearby power lines for running the equipment. These concerns are likely to incur initial costs that may lower the economic yields of the recovery methods unless the recovery sites are maintained for an extended period of time to offset these costs.

4.4 REE, Li, and Ga recovery from paleosols

The potential recovery of REEs and lithium from paleosols offers a promising avenue for diversifying supply and potentially improving sustainability in resource extraction. Paleosols are clay-rich rocks, and the liberation of REE by acid-leaching from these clay-rich rocks is expected to be easier than from difficult-to-leach coal ashes. For example, up to 90 % of total REE was bound as ion-adsorbed REEs in clay-rich rocks associated with coal in Pennsylvania (Rozelle and others, 2016).

The approaches to REE recovery are similar to those used for coal and coal refuse and they include:

- Acid leaching (sulfuric acid, citric acid, hydrochloric acid).

- Roasting with reagents followed by leaching: This involves heating the clays with various additives to transform the target elements into a more soluble form. Alkaline roasting and leaching can convert aluminosilicate matrix minerals into soluble species and decompose heat-resistant REE-bearing phosphate minerals, thereby enhancing the leaching recovery of REEs.
- Organic acid solution (OAS) leaching: A process involving treating REE-bearing paleosol with an OAS (containing organic acid and ionic salt) at specific temperatures and pH to separate the REE, forming a REE-yttrium concentrate.
- Calcination and leaching: Calcination (heating) can decompose certain REE-bearing minerals and promote the liberation of REE-bearing particles, improving their subsequent leaching recovery.

In a study of central Appalachian paleosols (Montross and others, 2020), paleosol samples with REE content of 250–353 ppm were sequentially extracted using ammonium sulfate $(NH_4)_2SO_4$, hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and the residual solids were subjected to lithium borate ($LiBO_2$) fusion and digestion. They conducted leaching experiments using various water-based leaching solutions. The solutions were composed of a combination of citric acid, sodium chloride, and conjugate buffer salt sodium citrate tribasic dihydrate. After sequential digestion, the dominant amount of REEs was bound in the non-extractable residual fraction containing 43–79 % of the total REEs. The analysis of different leachates revealed that the highest concentration of REEs was achieved by leaching with 0.1 M citrate solution amended with NaCl. They concluded that citrate is a chemically effective lixiviant that can be used to generate a pregnant leach solution (PLS) from clay-rich sedimentary rocks. Subsequent steps of purification and removing impurities such as Fe, Al, P, and Th are needed before REEs can be recovered. As with coal and coal waste, REE concentrations in the original paleosols are low (Mastalerz and others, 2022a), requiring the processing of larger volumes of material. This necessitates efficient and cost-effective recovery methods.

Studies on lithium recovery from bauxite mine tailings (Wu and others, 2023) indicate that Li could be extracted as lithium phosphate. In that study, Li_2O content in the original bauxite mine tailings was 0.20 %, and after leaching with mixed H_3PO_4 + H_2SO_4 (without roasting pre-treatment), the Li leaching rate reached 96 %. Using chemical precipitation, Li was separated from Al and Fe in the leachate by using H_2O_2 (hydrogen peroxide) and NH_3H2_O. Finally, Li was effectively precipitated as Li_3PO_4 by adding Na_2CO_3. The authors suggest that this procedure has potential to extract Li from low-grade Li resources.

There are no published examples of Ga recovery from paleosols, but studies were conducted on Ga-enriched tuffs in China (Zou and others, 2017). In that study, they used an alkaline sintering-water immersion-acid leaching method, consisting principally of three steps. In the first step, Ga-bearing minerals were decomposed by reacting with anhydrous sodium carbonate and converted into water-soluble or metallic acid compounds through the process of alkaline sintering under high-temperature calcining. In the second step, the soluble components in the post-calcination material were leached out by immersing in hot water and concentrated in the filtrate after filtration. In the last step, the filtration residue was leached using hydrochloric acid. In that study, both Ga and REEs were extracted in the same process.

A successful lithium recovery (up to 80 %) was achieved from montmorillonite-type clays using limestone-gypsum roasting and water leaching. In that process lithium silicate was converted to water-soluble lithium sulfate which was then recovered as lithium carbonate through precipitation (Lien, 1985).

Considerations for recovery of REE-CM from Indiana paleosols

Because many paleosols of Indiana are enriched in Ga (section 2.5.3), a combined REE and Ga recovery could be a suitable approach. In this approach (fig. 45), Ga-enriched filtrate is generated first, followed by acid leaching. Experiments with HCl and citrate solution amended with NaCl could give indications of which agent is more suitable for leaching Indiana paleosols. This combined Ga-REE recovery approach seems to be especially suitable for Indiana paleosols because: a) REE concentrations in Indiana paleosols are relatively low (on average 160–270 ppm); and b) a large portion of REEs is expected to reside in the non-extractable residual fraction. Consequently, Ga concentrations may be a very important element in making the decision about undertaking recovery. As our study suggests, if Al content in paleosol is above 12 %, there is a high possibility that Ga content will be more than 30 ppm, a threshold for an industrial-grade Ga deposit (see 2.5.3).

4.5 REE-CM recovery from black shales

Black shales are low-grade ore deposits. Historically, processing of black shales for critical mineral purposes includes: (1) Kupferschiefer Cu-Ag ore in Poland and Germany; (2) Ni-Mo-PGE polymetallic ore in the Cambrian Niutitang Formation in China; (3) Talvivaara/Terrafame Ni-Zn-Cu-Co ore in Finland; and (4) the Ranstad deposit from the Swedish Alum Shale (Vind and Tamm, 2021). Currently, only Talvivaara/Terrafame ore processing is operational. However, the host rock in Talvivaara/Terrafame is actually a black

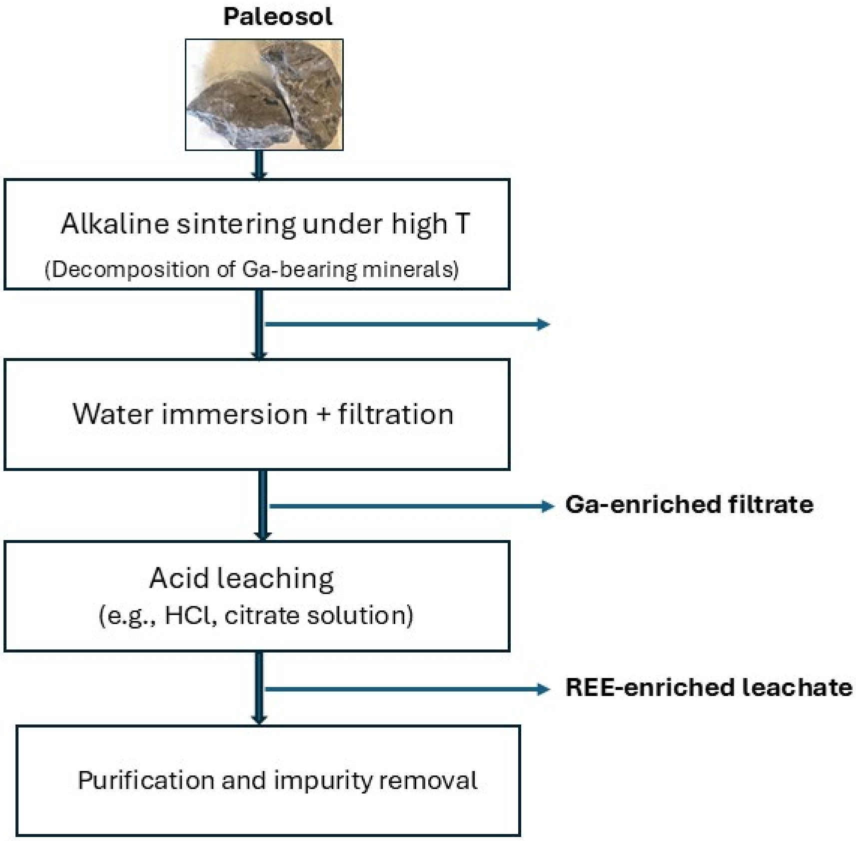


Figure 45. Schematic diagram of the alkaline sintering-water immersion-acid leaching process proposed for Ga and REE recovery from paleosols.

schist (metamorphic rock derived from shales) and not "typical" black shale.

Because of the fine-grained nature of black shales and the disseminated nature of trace metals in the various phases of the rock matrix, the beneficiation process is extremely difficult. Black shales are first crushed to small particles, <8 mm in Talvivaara/Terrafame (Riekkola-Vanhanen, 2013) and < 2 mm in Ranstad (Andersson, 1976). So far no flotation technology has been found that applies to black shales. Two approaches that target sulfides or organic matter have been tested (fig. 46; Kamradt and others, 2012; Orberger and others, 2018).

Leaching of trace metals into solutions is the next step of recovery. Common leaching methods include acid leaching (e.g., H_2SO_4, HCl, and HNO_3) and alkaline leaching; the latter is more effective for U and Mo. H_2SO_4 leaching is one of the most common methods used for black shale leaching (fig. 47) because of the generation of H_2SO_4 from pyrite oxidation. In-situ leaching could be suitable for deeply buried ore deposits that are technologically difficult or economically infeasible to excavate. Bioleaching employs microbes to extract trace metals from low-grade ore deposits (Bhatti, 2015; Johnson, 2018). However, bioleaching has more external factors than classical hydrometallurgy such as pH, temperature, and redox potential (Vind and Tamm, 2021).

The Pennsylvanian black shales in Indiana are rich in V, Zn, U, and Mo. Because Zn occurs in sphalerite, flotation targeting sulfide could be effective. Vanadium occurs in illite and organic matter and U is associated with organic matter. H_2SO_4 leaching at elevated temperatures (~ 100°C) could be effective. For Mo, alkaline leaching should be considered.

4.6 REE-CM recovery feasibility considerations

Any evaluation of the feasibility of recovering critical materials from coal-based material needs to consider both advantages and shortcomings of such operations. On the advantage side, the coal-based waste materials have little or no mining costs, are typically enriched in REE-CM compared to the original coal or the upper continental crust, and have the potential to mitigate or eliminate legacy environmental issues. Despite these advantages, there are, however, technical, economic, and environmental issues that need to be resolved to fully validate existing extraction technologies (Zhang and others, 2020a).

Numerous studies show that the economic feasibility and environmental impacts of employing any REE

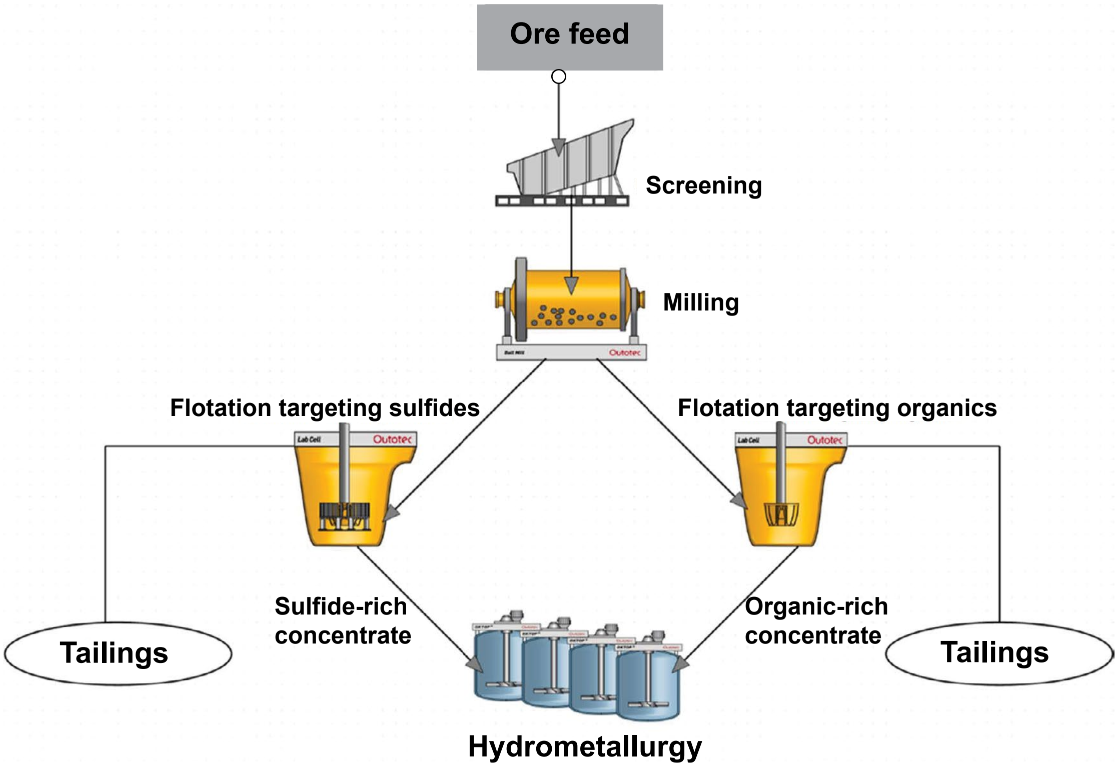


Figure 46. Simplified flowsheet of ore flotation approaches (from Vind and Tamm, 2021).

extraction technology from coal-based waste streams depends to a large extent on the feedstock properties and the level of REE enrichment they contain (Murty and others, 2024). This is why the main challenge to designing robust extraction systems that would be practical and economical is the low content of REEs and other critical minerals in most coal-based materials. However, coal-based materials also contain a range of other elements (e.g., Al, Ga, Ge, Ni, Li, and Zn) of economic interest, which could be co-extracted to add economic value. This co-production may be crucial for developing a sound business that could be protected from the volatility of REE prices. A lack of a clear and consistent pricing structure for REEs is also a major complication in the economic evaluation of REE projects.

Several laboratory and small pilot-scale projects funded by the U.S. DOE demonstrated the technical feasibility of producing high-purity critical minerals, including REE from low-grade (~300 ppm) materials such as coal and coal byproducts. (U.S. Department of Energy, 2022). Those projects exceeded the initial U.S. DOE requirement of 2 % purity within several months, and then over the next three years, they were able to reach very high REE recovery (99 wt % purity). These projects used a combination of physical and chemical separation techniques in the recovery process.

In contrast to pilot-scale projects, no comprehensive techno-economic studies of large-scale REE-CM recovery from low-grade feedstock have been published; most studies are based on small-scale experiments. Specifically, with respect to coal preparation plant refuse and coal ash, the published analyses suggest that extraction and recovery of high-purity rare earth products is technically feasible, and with proper optimization, processing cost can be reduced. For AMD precipitates, techno-economic analysis of REE extraction was conducted around select Appalachian coal mines as part of a U.S. DOE-sponsored project (Ziemkiewicz, 2019). In that evaluation, the consumption of chemicals in leaching accounted for 41 % of the total operating costs, followed by solvent extraction (SX) circuits (17 %), and precipitation (16 %). At the conclusion of the test, the operating expenses exceeded cash revenue by the order of magnitude. The capital cost (base equipment, installation, and contingency) of $35.6 million was largely driven by the leaching circuit. Further sensitivity analysis suggested that REE feedstock grade and leaching recovery were the two most influential parameters on the total cost. Consequently, a pre-concentration unit was developed and tested, and this resulted in a significantly improved feedstock quality and contributed to a reduction of the processing costs, meeting the economic thresholds (Ziemkiewicz, 2019).

In essence, to be competitive in the current economy, the cost of producing REE-CM from low-grade materials needs to be reduced. This high cost, and consequently

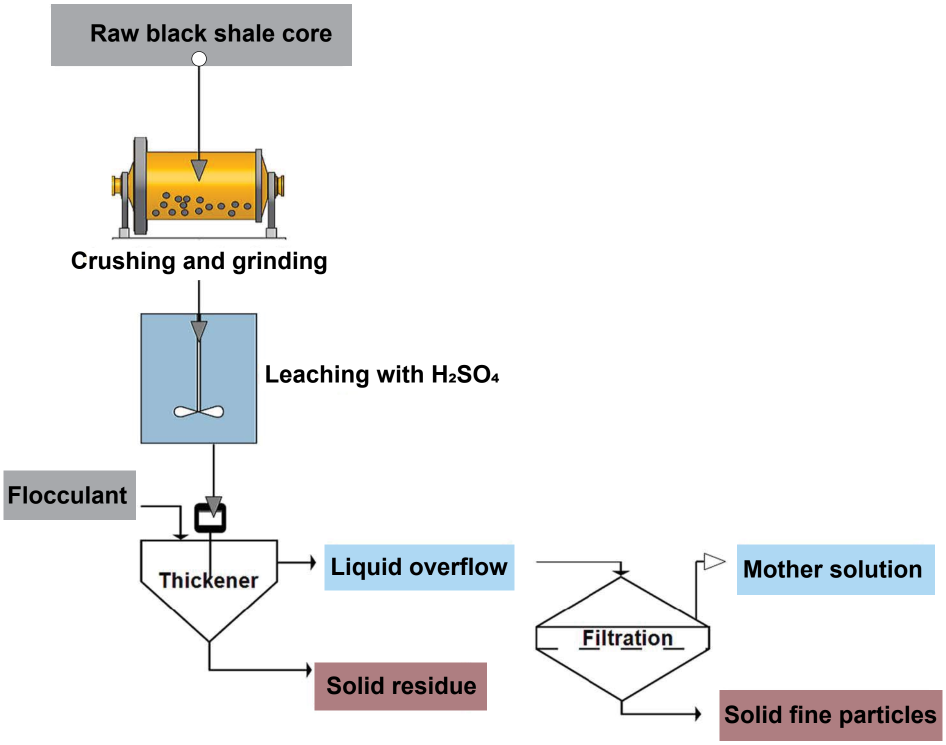


Figure 47. General flowsheet for black shale ore H_2SO_4 leaching processing (from Kim and others, 2014; Vind and Tamm, 2021).

the necessity to secure large investments, is the greatest challenge in attracting industries to undertake REE-CM recovery projects. The possibilities that need to be explored to lower costs include but are not limited to:

1. Reducing acid cost by replacing costly acids with ones that are less costly, yet still effective in leaching chemicals;
2. Recycling major reagents, thus reducing quantities of chemicals and waste disposal needs;
3. Improving pre-concentration techniques before leaching (e.g., roasting);
4. Increasing the effectiveness of physical pre-concentration;
5. Making co-production of multiple metals profitable; and
6. Producing higher-value coal products (activated carbon, humic acid, graphite) from high-carbon-content coal refuse.

As already mentioned, comprehensive economic assessments of REE-CM recovery projects on low-grade materials can only be possible when larger projects yield data suitable for robust economic analysis. To properly evaluate the expected return on investment for each REE, reliable data on extraction costs are required. These costs vary considerably by location and depend heavily on the scale of the operation. Consultation with industry experts is, therefore, essential for any meaningful assessment. Appendices 3 and 4 list prospective contacts: companies and individuals involved in REE and critical mineral extraction in Indiana (Appendix 3) and other U.S. states (Appendix 4).

Until such data are available, various extractability and cost aspects versus opportunities need to be considered, taking into account the feedstock properties. Another factor to consider is that any technology implemented to extract REE-CM from coal waste will create additional byproducts which will need to be handled and disposed of in an environmentally sound manner, adding to the overall project cost. Therefore, in-depth studies should evaluate the full economic and environmental costs and benefits of waste reprocessing activities, and the technologies that are the most economically feasible and environmentally advantageous should be promoted.

Considering the composition of coal-based materials of Indiana, Tables 27–30 present economic considerations associated with potential REE-CM recovery from coal fine-grained refuse (coal tailings, slurry), coarse-grained refuse (gobs), AMD, and coal ash. In addition to these general considerations, based on the volumes of the available coal waste, concentration of individual rare earth elements, and their prices, Tables 31 and 32 present approximate values of the elements currently residing in the coal slurry ponds and coal ash impoundments in Indiana. These tables split REEs into critical (Pr, Nd, Tb, Dy) and not critical (remaining REEs) categories from the perspective of supply risk. They also report prices, estimated volumes, and expected values for each REE. Among the uncritical REEs, scandium (Sc) stands out with by far the highest potential expected value—about $4.5 billion both for slurry and coal ash—driven largely by its extremely high price of $2,932 per kilogram. The second-highest expected value belongs to a critical REE, neodymium (Nd), with an estimated value of $273 million in slurry and $355 million in coal ash at a price of $76 per kilogram. All REEs combined have an estimated potential of $5.8 billion in slurry and coal ash. We note that that Indiana power plants produce ~5 million tons of coal ash each year, adding approximately ~$800 million in potential value of rare earth elements annually. These element values are very rough estimates only; the volatility of REE prices may change these estimates dramatically.

5. GEOPOLITICAL CONSIDERATIONS OF REE RECOVERY AND THE IMPORTANCE OF THE STATE'S INVOLVEMENT

Rare earths have become a form of geopolitical currency. China dominates the upstream and midstream of these supply chains and is the United States' primary source. According to the USGS, about 70 % of U.S. imports of rare-earth compounds and metals came from China between 2020 and 2024 (U.S. Geological Survey, 2025), and for the Harmonized System 6-digit code 280530 "Rare-earth metals, scandium and yttrium", virtually all 2023 U.S. imports were sourced from China (World Integrated Trade Solution, accessed August 2025). Recent headlines underscore how these levers get used alongside semiconductor controls rather than as a simple quid-pro-quo. In August 2025, Reuters reported that the Commerce Department in Washington began licensing Nvidia's H20 A.I. chips for sale to China—part of a broader easing of tensions (Reuters, Aug. 8, 2025)—while earlier reporting noted that the government in Beijing granted temporary export licenses for rare-earth magnets to suppliers serving major U.S. automakers. Together this signals a tactical thaw without erasing mutual dependencies (Reuters, Aug. 8, 2025). A useful way to frame this comes from a National Bureau of Economic Research paper by Clayton and others (2025) "Putting economics back into geoeconomics." They model export controls as "threats not to sell," analytically equivalent to imposing very high (even infinite) taxes, and show that the coercive power of such threats hinge on how easily the target can substitute away from the choke-pointed inputs. Where the substitution is hard (such as rare-earth processing), the leverage is high; where alternatives exist, leverage fades. Putting these pieces together means that China's concentration

Table 27. Potential economic considerations associated with REE-CM production from fine coal preparation plant waste (slurry, fine tailings).

Composition	Critical mineral consideration	Extractability and cost considerations	Circular economic considerations
- Fine particles of coal and rocks - Coal fraction dominated by vitrinite and inertinite, reflecting the composition of the original coal - Mineral fraction dominated by clays; sulfur content can vary, depending on its content in the original coal	- Carbon content varying between 20 and 50 wt % - Content of REEs is in the 200–600 ppm range and ~ 400 ppm on average (ash basis) - Other elements of interest are Ga (30 ppm on average), Ge (30–50 ppm on average), Zn (260–450 ppm on average), V (~ 180 ppm on average) - REEs and Ga show a positive correlation with aluminum	- Organic fraction (in coal fragments) can be isolated based on lower density - Using the DOE REE benchmark of 300 ppm for economical profitability, much of this material presents potential - Co-extraction of REEs with other elements (V, Cr, As, etc.) is possible, but separation is very costly	- Carbon has commercial value as a source of carbon ore and as a source of energy - Decarbonized material has commercial potential if appropriate technologies for REE-CM extraction are available - Waste utilization and waste reclamation could result in economically valuable uses of those areas - Clay-rich material can be used as cost-effective construction material - Kaolinite-rich material can be used in geopolymer production

Table 28. Potential economic considerations associated with REE-CM production from gob piles at abandoned mine lands.

Composition	Critical mineral consideration	Extractability and cost considerations	Circular economic considerations
- Coarse and variable-size rock fragments - Variable degree of weathering expected - Variable clay mineral content - Low carbon content, usually less than 10 wt % - Variable sulfur content, reflecting the original material	- REE content is variable, but often higher than in the fine refuse; however, sparse elemental data are available on gob piles from Indiana - Other elements of interest may include Li, Al, Mn, Rb, and Ba	- Using the DOE REE benchmark of 300 ppm for economical profitability, much of this material is expected to present potential; however, more data are needed on gobs to better assess their potential - Contamination with Fe, Al, and other chalcophile elements can add acid and base costs in the downstream extraction process - Co-extraction of REEs with other elements (V, Sr, R, Sb, Cs) is possible and could lower the cost of recovery; however, the cost of element separation may be substantial	- Considering high volumes, gobs may have commercial potential as REE-CM sources, provided elemental concentrations exceed the accepted benchmark - Waste utilization and waste reclamation could result in economically valuable uses of those areas - Clay-rich waste has potential as construction material, possibly offsetting the cost of extraction

in rare-earths and the U.S. control over leading-edge A.I. chips create reciprocal pressure points. Periodic licensing of Nvidia's China-compliant parts (H20-class) on one side and selective rare-earth licensing on the other fit the paper's prediction that states mix "sticks" with calibrated "carrots" to extract concessions while testing how substitutable each dependency really is (Reuters, Aug. 8, 2025).

Three key factors contribute to the dominance of China in processing REEs. First, the Chinese government provides extensive support to the sector through subsidies, export controls, and streamlined administrative approvals, enabling Chinese exporters to undercut international rivals. Western competitors face higher production costs due to environmental and regulatory constraints (Reuters, July 17, 2025; AP News, June 12, 2025; Baker Institute, December 19, 2022).

Second, Chinese firms operate at very large scales, which lowers per-unit costs and reinforces concentration. At present, China controls close to 90 percent of global REE processing capacity (Resources for the Future, 2025).

Third, China has historically tolerated environmentally harmful processing methods that would not be feasible in the United States or other developed economies with stricter regulations (Time, June 17, 2025; Baker Institute, December 19, 2022).

To overcome China's dominance in rare-earth processing, federal and state governments can pursue a state-led industrial strategy that combines large-scale public investment with coordinated private-sector partnerships. On the investment side, federal and state governments could deploy subsidies, loan guarantees, and contracts for difference (CFDs) to support domestic rare-earth processing facilities. Such measures reduce the high capital risk and slim profit margins that have historically deterred private players. Examples include Pentagon floor-price guarantees for strategic minerals and Japanese and French public investments in processing plants (Reuters, July 17, 2025; CSIS, July 28, 2025). At the same time, governments can strengthen public-private partnerships and form strategic industry consortia, modeled on China's Rare Earth Group, to better align incentives, pool resources, and consolidate fragmented supply chains. Such collaborative models, which bring together state entities, private firms, and research institutions, are discussed by the Oxford Institute for Energy Studies (2023) and the Baker Institute (2022).

6. ENVIRONMENTAL CONSIDERATIONS IN COAL WASTE REUSE AND REE-CM EXTRACTION

The reuse of coal waste and the extraction of rare earth elements and critical minerals (REE-CM) present Indiana with both opportunities and responsibilities. These activities can transform legacy byproducts of coal mining and power generation into valuable inputs for advanced manufacturing, including the semiconductor supply chain. At the same time, they introduce new operational and regulatory considerations that must be addressed to ensure safe, efficient, and commercially viable deployment.

Table 29. Potential economic considerations associated with REE-CM production from acid mine drainage (AMD).

Composition	Critical mineral consideration	Extractability and cost considerations	Circular economic considerations
- Aqueous mine drainage is highly acidic - It has elevated concentrations of sulfate, metals (Fe, Al, Ca), and trace metals (e.g., REE, Zn, Ni, Co, V, Cu, As)	- Concentration of REEs can vary from ppb to low ppm levels - AMD is enriched in critical (high-value) REEs (Nd, Eu, Tb, Dy, Er) - REEs are in solution	- REE-CM are already in solution, thus lowering the extraction cost - The capital costs of building AMD remediation systems are relatively high - Currently used approach to capturing and treating AMD can enrich REE content several thousand times, producing precipitates with concentrations above 1,000 ppm	- The extraction and commercialization of AMD byproducts could help cover the cost of AMD treatment - Even if it is not profitable to just produce REEs, public funding to remediate AMD could be used to offset the cost; for instance, the Clean Water Act requires treatment, and state reclamation funds might be available to remediate AMD

Table 30. Potential economic considerations associated with REE-CM production from coal ash.

Composition	Critical mineral consideration	Extractability and cost considerations	Circular economic considerations
- Aluminosilicate glass dominates the composition (60–90 %) - Crystalline phases include quartz, mullite, hematite, magnetite, spinel, and other minerals	- Enrichment of REEs is high compared to the original coal (REE is dominantly associated in the mineral fraction) - Higher proportions of critical REE (including Nd, Sc) are in total REEs than many conventional REE deposits - Residual ash (post-REE extraction) is still marketable to industry (e.g., cement)	- Coal ash occurs as powder, which eliminates grinding (thus energy) costs relative to typical REE processing - Profitability will be dependent on the proportion of critical (high value) to non-critical REEs - Difficult-to-leach and extract aluminosilicates require a lot of strong and costly acids	- Commercialization of fly ash reduces the need for storage - Reclamation of land on old coal ash repositories is beneficial - Mitigation of potential elimination of legacy environmental issues is beneficial - With a lot of environmental concerns about coal ash, public perception of risk versus benefits needs to be evaluated

Indiana already maintains a strong regulatory framework for coal refuse and coal combustion residuals (CCR), grounded in federal statutes and state-level implementation. These programs provide stability and predictability for operators. However, the processes required for REE-CM recovery—such as excavation, transport, pre-concentration, chemical extraction, and purification—extend beyond the scope of existing rules. Current oversight is primarily designed for coal mining and CCR disposal, leaving potential gaps when these materials are reprocessed for mineral recovery.

This section reviews the regulatory landscape and its implications for REE-CM recovery in Indiana. It highlights how coal refuse (Section 5.1) under the Indiana Department of Natural Resources (IDNR) and coal ash (Section 5.2) under the Indiana Department of Environmental Management (IDEM) are currently managed and identifies areas where existing rules may or may not align with the requirements of mineral recovery. The goal is to clarify the regulatory baseline, outline potential challenges, and position Indiana to leverage its permitting certainty and business-friendly environment as a competitive advantage in developing a full life cycle—from coal waste to chip fabrication—within the state.

The review covers:

- Coal refuse (IDNR): Long-term risks associated with pyrite-driven acid mine drainage (AMD) and

Table 31. Estimated REE concentrations and quantities from Indiana coal slurry and tailings. For this estimate, we assume that 120,000,000 metric tons are available for utilization in Indiana. Prices of metals are from April 23, 2025 (https://mineralprices.com).

REE	Concentration (ppm, whole-rock basis)	Element amount (in kg)	Metal price $/kg	Total value ($) in Indiana coal slurry deposits
Critical with regard to supply risk				
Pr	9	1,080.00	83	89,640,000
Nd	30	3,600,000	76	273,600,000
Tb	1	84,000	1,229	147,480,000
Dy	4	480,000	298	143,040,000
Critical total				653,760,000
Not critical with regard to supply risk				
Sc	13	1,560,000	2,932	4,573,920,000
La	30	3,600,000	3	10,800,000
Ce	63	7,560,000	4	30,240,000
Sm	5	600,000	9	5,400,000
Eu	2	240,000	28	6,720,000
Gd	8	960,000	200	192,000,000
Ho	1	120,000	63	7,560,000
Er	2	240,000	800	192,000,000
Tm	0.7	84,000		
Yb	2	240,000		
Lu	0.7	84,000	1,500	126,000,000
Y	17	2,040,000	34	69,360,000
Not critical total				5,214,000,000
Critical + not critical total				5,867,760,000

the federal and state reclamation mechanisms that govern storage, stabilization, and reuse.

- Coal ash (IDEM): The evolving framework shaped by the EPA's 2015 Coal Combustion Residuals (CCR) Rule, Indiana's historic implementation of solid waste and regulations, and adoption of national standards, with attention to groundwater protection, impoundment closure, and legacy sites.
- Cross-cutting issues: Gaps in regulatory coverage for REE-CM recovery, reliance on general environmental statutes such as the Clean Water Act, Resource Conservation and Recovery Act (RCRA), and Indiana's air quality rules (327 IAC), and the need for pilot-scale studies to characterize new waste streams, evaluate and determine potential environmental impact or release mechanisms, and develop appropriate safeguards.

Table 32. Estimated REE concentrations and quantities from coal ash in Indiana. There are ~52,566,153 m^3 of coal ash (~36,796,307 tons) in Indiana. In addition, on average, every year Indiana power plants produce ~5,000,000 tons of coal ash. Prices of metals are from April 23, 2025 (https://mineralprices.com).

REE	Concentration (ppm, whole-rock basis)	Element amount (in kg)	Metal price $/kg	Total value ($) in Indiana coal slurry deposits
Critical with regard to supply risk				
Pr	9	1,080.00	83	89,640,000
Nd	30	3,600,000	76	273,600,000
Tb	1	84,000	1,229	147,480,000
Dy	4	480,000	298	143,040,000
Critical total				653,760,000
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Sm	5	600,000	9	5,400,000
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Gd	8	960,000	200	192,000,000
Ho	1	120,000	63	7,560,000
Er	2	240,000	800	192,000,000
Tm	0.7	84,000		
Yb	2	240,000		
Lu	0.7	84,000	1,500	126,000,000
Y	17	2,040,000	34	69,360,000
Not critical total				5,214,000,000
Critical + not critical total				5,867,760,000

6.1 Environmental aspects of storage and utilization of coal preparation plant refuse

Coal preparation plant refuse is a legacy byproduct of Indiana's coal industry. It often contains significant amounts of pyrite, which, when exposed to water and atmospheric oxygen, generates acidic conditions. Unreclaimed deposits can remain barren of vegetation for an extended period, creating longterm environmental liabilities. At the same time, coal refuse has been shown to contain measurable concentrations of REE-CM, positioning it as both a challenge and a potential resource for advanced manufacturing supply chains.

The Surface Mining Control and Reclamation Act (SMCRA, 1977) required coal mine operators to reclaim waste deposits once mining ceased, while the Abandoned Mine Lands (AML) program was established to address legacy sites left unreclaimed. In Indiana, under authorizations issued by the IDNR, most refuse deposits have since been stabilized and revegetated, typically by capping with soil, synthetic soil, or spoil, or by applying agricultural limestone. These measures have reduced immediate hazards, but once an AML project is completed or a reclamation bond is released, no specific protections exist to prevent renewed excavation of these waste structures.

The IDNR has historically allowed for some disposal of the generated coal ash to be used as coal mine fill under nonruled policies approved by the Indiana Natural Resources Commission. Memorandum 921 governs disposal of ash in surface mines, whereas Memorandum 992 addresses beneficial reuse. Because of the interplay between IDNR and IDEM with coal waste, it is worth noting that IC 13-19-3-3 states that IDEM cannot regulate CCR used as mine subsidence, mine fire control, and mine sealing except as provided in federal CCR regulations.

Importantly, REE-CM recovery is not a regulated activity under current law. In practice, only general provisions under the Clean Water Act (327 IAC 2) and Indiana's Air Quality rules (326 IAC) would apply. If recovery were conducted as part of an active coal mining operation, it would need to fall under the associated coal mining permit issued by the IDNR. In the absence of regulations specific to REE-CM recovery, regulators would need to determine on a casebycase basis whether additional oversight or permit conditions may be warranted as they relate to coal refuse. Indiana's permitting certainty and established regulatory programs provide a strong foundation for clarifying these pathways, which is essential for attracting investment in recovery projects (Table 33).

These laws and regulations also apply to acid mine drainage (AMD) sites, which remain a concern in Indiana. Key measures include controlling discharges, treating contaminated waters and precipitates, and restoring mined areas to prevent long-term damage. If REECM extraction were pursued at AMD sites, disposal of leach residues would require careful evaluation. Such residues are expected to resemble conventional AMD sludge (Ziemkiewicz, 2019). Although solvent extraction precipitates are likely to be low in volume, they may require specialized handling, and postextraction acids and bases would need neutralization. The true extent of environmental risks from these streams can only be assessed once pilotscale, continuous operations generate sufficient material for developing proper characterization, handling, and disposal specifications and considerations.

Over the past three decades, passive treatment systems have been widely used in Indiana to mitigate AMD. These systems—such as anoxic limestone drains, vertical flow ponds (VFPs), successive alkalineproducing systems, sulfatereducing bioreactors (SRBs), oxidation ponds, and anaerobic wetlands—require little ongoing monitoring and no chemical inputs. When functioning properly, they can meet NPDES discharge requirements. Performance and longevity of the treatment systems, however, has been variable: some systems remain effective for years, while others fail within a short time.

In 2012, samples were collected from two systems (VFP and SRB) to compare inflow versus outflow REE concentrations (Table 34). Results show rather irregular retention of light versus heavy REEs, as indicated in the L/H ratio (light/heavy) column of Table 34 compared to the ratio in the AMD seeps prior to treatment, along with notable retention of yttrium (Y). More data are needed to better understand retention of light versus heavy REEs as a result of the application of passive treatment systems.

Both VFPs and SRBs require periodic replacement of their substrates. This creates an opportunity to recover REEs from the spent material using methods described in Section 3. However, unless REE concentrations are sufficiently high, the costs of excavation, transport, and processing may outweigh potential economic benefits. Pilotscale testing will be essential to determine whether Indiana's coal refuse deposits and AMD treatment systems can support commercially viable recovery within the state.

6.2 Environmental aspects of coal ash storage and utilization

Coal combustion residues (CCRs), commonly referred to as coal ash, are one of Indiana's most significant industrial byproducts. They are predominantly managed under the IDEM through issued permits for disposal in landfills and closure approvals in surface impoundments within the property owned by the coal-fired power plants. A portion of Indiana's coal ash is also beneficially reused in concrete and construction materials, demonstrating a long regulatory history in Indiana of working with generating facilities on viable alternatives to permanent waste disposal and providing an established foundation for CCR and its potential as a secondary resource. Separately, as noted in Section 6.1, the IDNR has historically allowed some placement of CCR as coal mine fill.

Coal ash is of particular interest for rare earth element and critical mineral (REE-CM) recovery because fly ash and bottom ash can contain measurable concentrations of rare earths, enriched in comparison to the coal feed. Indiana has the largest number of CCR impoundments in the U.S. and a significant amount of CCR landfills. This positions Indiana as one of the country's largest sources of coal ash. As such, CCR has great potential as a feedstock for advanced manufacturing supply chains. However, based on IDEM's historical oversight of regulated and unregulated CCR disposal areas, improper management of CCR can pose risks to water quality

Table 33. Timeline of regulations governing coal mining and preparation plant waste (coal refuse) management in Indiana.

Year	Regulation/Action	Description
1941	Indiana's first coal mining regulation	Indiana enacted its first law regulating coal mining, marking the state's initial efforts to address environmental impacts of mining activities.
1977	Surface Mining Control and Reclamation Act (SMCRA)	Federal law establishing nationwide standards for coal mining and reclamation; Indiana later developed its own program under this framework.
1982	Indiana's SMCRA implementation	Indiana's Department of Natural Resources (DNR) began implementing SMCRA standards, overseeing coal mine reclamation within the state.
2003	Indiana Regulatory Program Amendment	The Office of Surface Mining Reclamation and Enforcement approved amendments to Indiana's regulatory program, enhancing groundwater protection measures.

due to releases of trace elements such as arsenic, boron, cobalt, lithium, and molybdenum (Frank and Maloney, 2020). This material, like other industrial wastes, can create waste management challenges for both the facility and the regulator. However, based on IDEM's long regulatory history with coal ash, these challenges have been mostly overcome.

Therefore, regulating the proper management of CCR, including storage, processing, and disposal, needs to be implemented in a manner that is protective to human health and the environment. Any processes proposed for the extraction of REE-CMs will need to be designed, constructed, and implemented with proper engineering controls and adequate monitoring. Avenues and mechanisms currently exist through IDEM's permitting programs for the development of practical modifications to existing landfill permits or impoundment closure approvals for implementing REE-CM extraction in a manner protective to human health and the environment.

6.2.1 Regulatory evolution

Prior to 2015, IDEM primarily oversaw the implementation of Indiana's solid waste rules and guidance/policy for the management and disposal of coal ash in landfills and impoundments. However, due to exemptions listed under 329 IAC 10-3-1-8, closure requirements (including monitoring) for coal ash impoundments were deferred until after their removal from a state water pollution control permit (i.e., NPDES permit). The regulated disposal of CCR in landfills in Indiana has been implemented under IDEM's 329 IAC Rule 10-29 and its solid waste regulatory predecessors (Table 35). The illegal disposal of CCR also has a long regulatory history under IDEM's open dumping rule under 329 IAC 10-4 and its solid waste regulatory predecessors (Table 35).

The EPA's 2015 Coal Combustion Residuals (CCR) Rule established national standards for siting, design, and operation of CCR units to reduce risks of structural failure and contamination. In response, Indiana's Environmental Rules Board adopted the CCR Rule for surface impoundments in 2016.

Table 34. AMD treatment systems showing disproportionate retention of heavy REE (HREE) over light REE (LREE) and retention of yttrium (Y). Units for LREE, HREE, and Y are in micrograms per liter.

Site	LREE	HREE	L/H ratio	Y
Enos Seep	98	17	5.7	35
Enos VFP	1.4	0.17	8.2	0.28
Enos SRB	0.5	0.12	4.2	0.34
Lacy Seep	230	97	2.4	156
Lacy SRB	1.4	0.29	4.8	1.0
Midwestern Seep	206	73	2.8	160
Midwestern SRB	18	3.7	4.9	11.2

Also in 2015, the EPA issued the Effluent Limitation Guidelines (ELG) Rule under the Clean Water Act, setting limits on contaminants in wastewater discharges from coal ash management. Implementation was delayed in 2017, and revisions finalized in 2020 relaxed some of the original discharge limits. Even so, the CCR and ELG Rules prompted most Indiana coal-fired power plants to transition away from wet disposal in impoundments and toward dry handling systems and landfills. Some impoundments that failed siting or design standards were required to close immediately. In January 2022, the EPA issued clarifications to strengthen portions of the CCR Rule, and in May 2024, finalized new requirements for legacy CCR surface impoundments, extending compliance obligations to inactive facilities.

Table 35 outlines the key milestones in federal and state coal ash regulation, from the Resource Conservation and Recovery Act (RCRA, 1976) and the Bevill Amendment (1980) through IDEM's Solid Waste Disposal Facility Rule promulgated under 329 IAC 10 (1996), the 2015 CCR Rule, and the 2024 legacy impoundment amendments. These rules have steadily advanced the environmentally sound management of CCR.

Table 35. Timeline of regulations governing coal ash management in the United States.

Year	Regulation/Action	Significance
21-Oct-76	Resource Conservation and Recovery Act (RCRA)	Established framework for solid waste management; CCRs initially exempted from hazardous waste rules pending further study.
1980	Solid Waste Disposal Act Amendments (Bevill Amendment)	Temporarily exempted CCRs from hazardous waste regulation under RCRA Subtitle C, pending EPA review.
2-Aug-13	EPA Notice of Data Availability	Requested additional data on CCR disposal, large-scale fill, and impoundment structural integrity.
19-Dec-14	EPA Final Rule on CCR Disposal	Established comprehensive national requirements for CCR disposal under RCRA Subtitle D.
17-Apr-15	Publication of Final CCR Rule	Set minimum criteria for CCR landfills and impoundments, including siting, design, groundwater monitoring, corrective action, closure, and post-closure care.
2-Jul-15	EPA Correction to CCR Rule	Adjusted effective date of the CCR Rule to October 19, 2015.
5-Aug-16	EPA Extension for Inactive Impoundments	Extended compliance deadlines for certain inactive CCR impoundments following court rulings.
Jan-22	EPA Clarifications to CCR Rule	Strengthened enforcement and clarified compliance requirements.
8-May-24	EPA Final Rule on Legacy CCR Impoundments	Required owners of legacy impoundments at inactive utilities to comply with most CCR requirements, except siting and liner design criteria.

6.2.2 Implications for REE-CM recovery

While these regulations provide a strong baseline for environmentally sound CCR disposal and management, they do not directly address the environmental impacts of excavating and processing coal ash for REE-CM extraction and recovery. For REE-CM recovery, there are several avenues for obtaining and processing the CCR from the IDEM-regulated disposal facilities via modifications to requirements specified in IDEM-issued landfill permits or in IDEM-approved impoundment closure approvals. Under IDEM authority, Indiana has permitted multiple landfills that were designed, or had their permits modified to allow for, the removal, processing, and utilization of industrial waste previously disposed under 329 IAC 10-29 rules.

Avenues and mechanisms currently exist through IDEM's permitting programs for the development of practical modifications up to and including financial assurance requirements to existing landfill permits or impoundment closure approvals for implementing REE-CM extraction in a manner protective of human health and the environment. However, leaching, refining, and other potential extraction processes may mobilize contaminants not currently regulated under CCR or IDEM rules. Therefore, additional regulatory clarity—or targeted incentives for onsite pilot studies—may be necessary to encourage utilities and private operators to pursue beneficial reuse of CCR for REE-CM extraction.

6.3 Synthesis: Overarching environmental and regulatory themes

Coal refuse and coal ash are two of Indiana's most significant legacy byproducts from coal mining and power generation. Both materials carry measurable concentrations of rare earth elements and critical minerals (REE-CM), positioning them as potential secondary resources for advanced manufacturing. However, the regulatory frameworks that govern these materials were designed primarily for waste containment and reclamation and not for the resource recovery.

Key crosscutting themes

- Regulatory gaps: Federal and state rules under SMCRA, RCRA, and the CCR Rule provide strong foundations for reclamation and disposal, but they do not directly address the environmental implications of remining or processing coal refuse or coal ash for REE-CM recovery. Indiana's permitting certainty offers a platform to clarify these pathways, but explicit guidance is still lacking.
- Environmental risks: Disturbance of stabilized refuse piles or legacy ash impoundments could generate acid mine drainage (AMD), mobilize trace metals, or release airborne particulates. Recovery processes themselves may create new waste streams—such as leach residues or solvent extraction precipitates—that require neutralization and safe handling.

- Reliance on general statutes: In the absence of REE-CM-specific rules, oversight would default to broad frameworks such as the Clean Water Act and Indiana's air quality standards (326 IAC). These provide important protections but may not fully capture the unique risks of mineral recovery activities.
- Need for pilot-scale data: Proper risk assessment and regulatory alignment will require pilot-scale operations to characterize waste streams, evaluate toxicity, and test treatment and disposal options. Data from AMD treatment systems in Indiana already suggest selective retention of REEs, but largerscale demonstrations are needed to confirm economic and environmental feasibility.
- Economic and policy considerations: The complexity of current regulations, combined with uncertainty about compliance pathways, may discourage operators from pursuing REE-CM recovery. However, avenues and mechanisms currently exist through IDEM's and IDNR's permitting programs for the development of practical modifications to existing landfill permits or impoundment closure approvals and abandoned mine and coal refuse, respectively, for implementing REE-CM extraction in a manner protective to human health and environment.
- However, leaching, separation, and other potential extraction processes may mobilize contaminants in coal ash or coal refuse, not currently regulated under federal or state rules. Therefore, additional regulatory clarity—or targeted incentives for onsite pilot studies—may be necessary to encourage utilities and private operators to pursue beneficial reuse of CCR and coal refuse for REE-CM extraction.

7. CONCLUDING COMMENTS AND RECOMMENDATIONS

This report assesses the technical and economic potential for extracting rare earth elements and other critical materials (REE–CM) in Indiana. The focus is on coal-related feedstocks (in-situ coal, preparation wastes, and coal ash) and selected sedimentary units (black shales; Pennsylvanian paleosols) as prospective sources. We summarize what is known about grades, processing routes, and co-product opportunities; identify the key cost drivers and risks; and outline actionable recommendations for the State of Indiana to catalyze private investment and responsibly advance REE-CM recovery.

Indiana's long history of coal mining has left behind large volumes of mining byproducts, making coal and coal-based products a central focus for evaluating potential sources of rare earth elements (REEs) and other critical minerals (CM). In addition to large reserves of in-situ (unmined) coal, Indiana's extensive coal preparation activities and coal combustion history have generated large volumes of fine tailings, coarse refuse, and coal ash. These waste materials, already mined and concentrated, could provide a lower-cost, strategically important pathway for domestic REE-CM production. In addition to coal-based materials, some geologic formations in Indiana also warrant attention. Pennsylvanian and Devonian black shales host critical metals such as vanadium and zinc, while Pennsylvanian paleosols have been suggested to be potential sources of lithium, gallium, and germanium. Enhanced sampling, characterization, and mapping of these geologic deposits, waste products, and other unexplored resources in Indiana will assist with the development of innovative extraction technologies. Taken together, Indiana's coal resources, mining wastes, and associated sedimentary units position the state as a potentially significant contributor to U.S. efforts to diversify critical mineral supply chains.

All the potential sources of REEs in Indiana are, however, low-grade resources with relatively low REE concentrations. Technologically, the extraction of the elements from such sources has been proven to be feasible, but costly. The co-production of other important elements (e.g., Al, Ga, Ge, Ni, Li, and Zn) may be crucial for developing a sound business that could be protected from the volatility of REE prices. Therefore, economic viability will depend on slashing processing costs, co-producing byproducts, and aligning with federal and state efforts to reduce reliance on Chinese supply chains.

Utilization of abundant coal preparation plant waste would mitigate Indiana's legacy environmental issues. The largest deposits in volume, those that resulted from processing the Springfield coal, should be the primary target for consideration. However, because of low concentrations of REEs in such materials and the high cost of the extraction, additional elements such as Ga, and additional beneficial uses for carbon and clays need to be evaluated to improve the economic outcome.

Acid mine drainage (AMD) from coal refuse and spoil ridges is a promising source of REE-CM. The benefits of REE-CM extraction from AMD are both economic and environmental. The economic side is the recovery of critical minerals, led by REEs but also other components. Another economic benefit would be the creation of jobs to install and maintain the extraction stations. The removal of both desired critical minerals as well as excess mineralization that degrades the quality of streams could bring both economic and environmental benefits.

Coal ash has been considered an important REE source. The concentration of REEs in coal ash is more favorable compared to the coal refuse. However, because in coal ash, REEs are concentrated in difficult-to-leach glassy aluminosilicates, harsh leaching conditions with concentrated acid solution at relatively high temperature will be required to achieve satisfactory recovery, resulting in a high cost of the project. Utilization of post-REE extraction residual ash (e.g., in the cement industry) could offset the cost of extraction. In general, comprehensive economic assessments of REE-CM recovery projects on low-grade materials can only be possible when larger projects yield data suitable for robust economic analysis. Additional regulatory clarity—or targeted incentives—may also be necessary to encourage utilities and private operators to pursue beneficial reuse of coal ash for critical mineral extraction.

Indiana maintains a strong regulatory framework for coal refuse and coal combustion residuals (CCR), grounded in federal statutes and state-level implementation. These programs provide stability and predictability for operators. However, the processes required for REE-CM recovery—such as excavation, transport, pre-concentration, chemical extraction, and purification—extend beyond the scope of existing rules. Current oversight is primarily designed for coal mining and CCR disposal, leaving potential gaps when these materials are reprocessed for mineral recovery.

We recommend that the future actions toward REE-CM extraction from Indiana resources include:

1. **Industry outreach:** Consult with industry specialists—and/or designate a university-led team—to gauge interest in REE-CM extraction in Indiana and identify priority partners/sites.
2. **Incentives:** Offer performance-based tax credits or refundable grants for pilot/demonstration plants that (a) process Indiana coal wastes/ash or AMD, (b) meet in-state spend and jobs thresholds, and (c) deliver the verified REE-CM output or intermediate concentrates.
3. **Fast-track, one-stop permitting:** Designate a single point of contact to coordinate IDEM, IDNR, INDOT, and local authorities for REE-CM pilots, and publish a permitting checklist specific to waste-to-minerals projects (remining, transport, process water, air permits, residuals reuse) to reduce timeline risk.
4. **Federal funding capture:** Pursue DOE, DOD/Title III, EDA, and EPA/USDA opportunities. Assign a grant-capture team to track solicitations, pre-qualify Indiana sites, assemble consortia (universities, utilities, operators), and align state match language in advance.

REFERENCES

References on Indiana

Allen, J. H., Thomas, T. C., and Kelley, R. R., 1978, Derelict lands of Indiana—a survey to determine the extent and environmental effect of derelict lands resulting from the surface extraction of coal, P.L. 62, Acts of 1976: Indiana Department of Natural Resources, 46 p.

Blatchley, W. S., 1896, A preliminary report on the clays and clay industry of the coal bearing counties of Indiana: Indiana Department of Geology and Natural Resources, 20th Annual Report, p. 24–185.

Blatchley, W. S.,1901, The mineral waters of Indiana: Indiana Department of Geology and Natural Resources 26th Annual Report, p. 11–226.

Callaghan, E.,1948, Endellite deposits in Gardner Mine Ridge, Lawrence County, Indiana: Department of Conservation, Division of Geology, Bulletin No. 1.

Drobniak, A., and Mastalerz, M., 2022, Rare earth elements—a brief overview: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 4. doi: https://doi.org/10.14434/ijes.v4i1.33628

Frank, I., and Maloney, T., 2020, Our waters at risk, part 2—the impact of coal ash on Indiana's water resources: Hoosier Environmental Council, 32 p.

Harper, D., Dintaman, C., Mastalerz, M., and Letsinger, S. L., 2009, Reconnaissance of coal-slurry deposits in Indiana: Indiana Geological Survey Occasional Paper 69, 20 p.

Harper, D., Olyphant, G. A., and Branam, T. D., 2012, Direct revegetation and the sustainability of reclaimed mine lands—the story of the Friar Tuck site, Indiana, in J.B. Comer, ed., Effects of abandoned mine land reclamation on ground and surface water quality—research and case histories from Indiana: Indiana Geological Survey Special Report 72, p. 83–126.

Hasenmueller, N. R., and Comer, J. B., 1994, Gas potential of the New Albany Shale (Devonian and Mississippian) in the Illinois Basin: Gas Research Institute, GRI-92/0391, Illinois Basin Studies 2, 83 p.

IndianaMap, 2022, Surface impoundments in Indiana [map feature layer]: IndianaMap website, <https://www.indianamap.org/datasets/INMap::surface-impoundments-in-indiana/explore?location=39.737501%2C-86.340513%2C7.48>.

INDR, 1978, Photo-interpretation handbook, vol. 1—methods and materials used for the identification of derelict lands associated with surface mining of coal in southwestern Indiana: Laboratory for Applications of Remote Sensing (LARS) Contract Report 022378, Purdue University.

Logan, W. N., 1922, Economic geology of Indiana: Handbook of Indiana Geology, Indiana Department of Conservation Publication 21, p. 571–1,058.

Logan, W. N. and Ries, H., 1922, Indianaite of Indiana: U.S. Geological Survey Bulletin, v. 708, p. 147–162.

Liu, B., Schieber, J., Mastalerz, M., and Teng, J., 2019, Organic matter content and type variation in the sequence stratigraphic context of the Upper Devonian New Albany Shale, Illinois Basin: Sedimentary Geology, v. 383, p. 101–120.

Mackey, J., Bain, D.J., Lackey, G., Gardiner, J., Gulliver, D., Kutchko, B., 2024. Estimates of lithium mass yields from produced water sourced from the Devonian-aged Marcellus Shale. Nature, Scientific Reports 14, 8813. https://www.nature.com/articles/s41598-024-58887-x

Mastalerz, M., Ames, P., Eble, C. F., Hasenmueller, N.R., Marietta, G., and Liu, B., 2024, Modifications of Pennsylvanian stratigraphy in Indiana: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 6. doi: https://doi.org/10.14434/ijes.v6i1.39762

Mastalerz, M., Branam, T., Douds, A. S. B., Beckham-Feller, V., Leffel, V. A., Hampton, L, and Marietta, G., 2025, Characterization of coal tailings from Indiana—implications for their potential utilization as sources of critical elements and carbon: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 7. doi: https://doi.org/10.14434/ijes.v7i1.40802

Mastalerz, M., and Drobniak, A., 2007, Arsenic, cadmium, lead and zinc in the Danville and Springfield Coal Members (Pennsylvanian) from Indiana: International Journal of Coal Geology, v. 71, no. 1, p. 37–53.

Mastalerz, M., and Drobniak, A., 2012, Gallium and germanium in selected Indiana coals: International Journal of Coal Geology, v. 94, p. 302–313.

Mastalerz, M., Drobniak, A., and Ames, P., 2022a, Organic-matter-rich Pennsylvanian black shales as a source of critical minerals: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 4. doi: https://doi.org/10.14434/ijes.v4i1.34421

Mastalerz, M., Drobniak, A., and Branam, T., 2022b, Coal and coal byproducts as potential sources of rare earth elements (REE) in Indiana: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 4. doi: https://doi.org/10.14434/ijes.v4i1.35307

Mastalerz, M., Drobniak, A., Ames, P., and McLaughlin, 2022c, Characterization of Pennsylvanian paleosols in Indiana with a special reference to rare earth (REE) and lithium: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 4. doi: https://doi.org/10.14434/ijes.v4i1.33975

Mastalerz, M., Drobniak, A., Eble, C., Ames, P., and McLaughlin, P., 2020, Rare earth elements and yttrium in Pennsylvanian coals and shales in the eastern part of the Illinois Basin: International Journal of Coal Geology, v. 231, 103620.

Mastalerz, M., Drobniak, A., Rupp, J. A., and Shaffer, N. R., 2009, Characterization of Indiana's coal resource—availability of the reserves, physical and chemical properties of the coal and present and potential uses: Indiana Geological Survey Special Report 66, 227 p.

Mastalerz, M., Hower, J. C., Drobniak, A., Mardon, S. M., and Lis, G., 2004, From in-situ coal to fly ash—a study of coal mines and power plants from Indiana: International Journal of Coal Geology, v. 59, no. 3-4, p. 171–192.

Mastalerz, M., and Padgett, P. L, 1999, From in-situ coal to the final coal product—a case study of the Danville Coal Member (Indiana): International Journal of Coal Geology, v. 41, p. 107–123.

Mastalerz, M., and Roden, N., 2023, Gallium and germanium in Pennsylvanian coals, shales, and paleosols in Indiana: Indiana Geological and Water Survey, Indiana Journal of Earth Sciences, v. 5. doi: https://doi.org/10.14434/ijes.v5i1.36455

Mastalerz, M., Schimmelmann, A., Drobniak, A., and Chen, Y., 2013, Porosity of Devonian and Mississippian New Albany Shale across a maturation gradient—insights from organic petrology, gas adsorption, and mercury intrusion: AAPG Bulletin, v. 97, p. 1,621–1,643.

Shaffer, N. R., 1981, Possibility of Mississippi Valley-type mineral deposits in Indiana: Indiana Geological Survey Special Report 21, 49 p.

Weismiller, R. A., and Mroczynski, R. P., 1978, Status of derelict land associated with coal mining in southwestern Indiana: Laboratory for Applications of Remote Sensing (LARS) Contract Report 022378, Purdue University.

Zangerl, R., and Richardson, E.A., 1963, The paleoecological history of two Pennsylvanian black shales: Fieldiana, Geology Memoir, 4, 352 p.

Other cited references

American Coal Ash Association, 2023, <https://acaa-usa.org/publications/production-use-reports/>.

Andersson, A., 1976, Uranium recovery from bituminous shales at Ranstad, in Uranium Ore Processing: International Atomic Energy Agency, p. 171–177.

AP News, June 12, 2025, Critical minerals give China an edge in trade negotiations, <https://apnews.com/article/trade-minerals-rare-china-trump-5f7c9b-9360cfb3cce702649e0c568a0e>.

Baker Institute, December 12, 2022, Of Chinese Behemoths: What China's rare earth dominance means for the US, <https://www.bakerinstitute.org/research/chinese-behemoths-what-chinas-rare-earths-dominance-means-us>.

Balaram, V., 2019, Rare earth elements—a review of applications, occurrence, exploration, analysis, recycling, and environmental impact: Geoscience Frontiers, v. 10, no. 4, p. 1,285–1,303.

Bhatti, T. M., 2015, Bioleaching of organic carbon rich polymetallic black shale: Hydrometallurgy, v. 157, p. 246–255.

Boxleiter, A., Wen, Y., Tang, Y., and Elliott, W. C., 2024, Rare-earth element (REE) remobilization and fractionation in bauxite zones from sedimentary kaolin deposits, western Georgia (USA), Upper Coastal Plain: Chemical Geology, v. 660, 122151.

Cao, S., Zhou, C., Pan, J., Liu, C., Tang, M., Ji, W., Hu, T., and Zhang, N., 2018, Study on influence factors of leaching of rare earth elements from coal fly ash: Energy & Fuels, v. 32, p. 8,000–8,005.

Center for Strategic and International Studies (CSIS), July 28, 2025, Developing rare earth processing hubs: An analytical approach, <https://www.csis.org/analysis/developing-rare-earth-processing-hubs-analytical-approach>.

Clayton, C., Maggiori, M., Schreger, J., 2025, Putting economics back into geoeconomics, <https://www.nber.org/papers/w33681>.

Coveney, R. M., 1979, Sphalerite concentrations in Mid-continent Pennsylvanian black shales of Missouri and Kansas: Economic Geology, v. 74, no. 1, p. 131–140.

Coveney, R. M., 2003, Metalliferous Paleozoic black shales and associated strata, in Lenz, D. R., ed., Geochemistry of sediments and sedimentary rocks—evolutionary considerations to mineral deposit-forming environments: Geotext 4, Geological Association of Canada, p. 135–144.

Coveney, R. M., and Glascock, M. D., 1989, A review of the origins of metal-rich Pennsylvanian black shales, central U.S.A., with an inferred role for basinal brines: Applied Geochemistry, v. 4, no. 4, p. 347–367.

Coveney, R. M., Goebel, E. D., and Ragan, Y. M., 1987, Pressures and temperatures from aqueous fluid inclusions in sphalerite from midwestern country rocks: Economic Geology, v. 82, p. 740–751.

Dai, S., and Finkelman, R. B., 2018, Coal as a promising source of critical elements—progress and future prospects: International Journal of Coal Geology, v. 186, p. 155–164.

Dai, S., Finkelman, R. B., Hower, J. C., French, D., Graham, I. T., and Zhao, L., 2023, Inorganic geochemistry of coal: Elsevier, Amsterdam, 438 p.

Dai, S.,Wang, X., Seredin, V. V., Hower, J. C., Ward, C. R., O'Keefe, J. M. K., Huang, W., Li, T., Li, X., Liu, H., Xue,W., and Zhao, L., 2012, Petrology, mineralogy, and geochemistry of the Gerich coal from the Wulantuga Ge ore deposit, Inner Mongolia, China—new data and genetic implications: International Journal of Coal Geology, v. 90–91, p. 72–99.

Elliott, W. C., 2021, A novel occurrence of the rare-earth elements in kaolin, Georgia Coastal Plain: presentation to U.S. Energy Association Gulf Coast Workshop, Critical Minerals Sustainability, <https://www.theassay.com/articles/analysis/south-australian-kaolin-miners-unveil-significant-ree-potential/>.

Finkelman, R. B., 1993, Trace and minor elements in coal, in Engel, M.H., and Macko, S.A., eds., Organic Geochemistry, Plenum, N.Y., p. 593–607.

Fu, B., Hower, J. C., Zhang, W., Luo, G., Hu, H., and Yao, H., 2022, A review of rare earth elements and yttrium in coal ash—content, modes of occurrences, combustion behavior, and extraction methods: Progress in Energy and Combustion Science, v. 88, 100954.

Gregg, J. M., and Shelton, K. L., 2012, Mississippi Valley-type mineralization and ore deposits in the Cambrian – Ordovician great American carbonate bank, in Derby, J.R., Fritz, R.D., Longacre, S.A., Morgan, W.A., and Sternbach, C.A., eds., The great American carbonate bank the—geology and economic resources of the Cambrian–Ordovician Sauk Megasequence of Laurentia: AAPG Memoir 98, p. 163–186.

Hatch, J. R., Gluskoter, H. J., and Lindahl, P. C., 1976, Sphalerite in coals from the Illinois Basin: Economic Geology, v. 71, p. 613–624.

Hatch, J. R., and Leventhal, J. S., 1985, Organic and trace element geochemical evidence of depositional and post-depositional processes for midcontinent Middle and Upper Pennsylvanian organic-matter-rich rocks, in Watney, R.L. Kasler, R.L., and Newell, K.D., eds., Recent interpretations of Late Paleozoic Cyclothems: Proceedings of the SEPM North Central Section 3rd Annual Conference, Lawrence, Kansas, p. 267–268.

Honaker, R. Q., Groppo, J., Yoon, R. H., Luttrell, G. H., Noble, A., and Herbst, J., 2017, Process evaluation and flowsheet development for the recovery of rare earth elements from coal and associated byproducts: Minerals & Metallurgical Processing, v. 34, p.107–115.

Honaker, R. Q., Zhang, W., and Werner, J., 2019, Acid leaching of rare earth elements from coal and coal ash—implications for using fluidized bed combustion to assist in the recovery of critical materials: Energy & Fuels, v. 33, p. 5,971–5,980.

Hower, J. C., Fu, B., Dai, S., and 2020, Geochemical partitioning from pulverized coal to fly ash and bottom ash: Fuel, v. 279, 118542.

Hower, J. C., Qian, D., Briot, N. J., Santillan-Jimenez, E., Hood, M. M., Taggart, R. K., and Hsu-Kim, H., 2019, Nano-scale rare earth distribution in fly ash derived from the combustion of the fire clay coal, Kentucky: Minerals, v. 9, no. 4, 206.

Johnson, D. B., 2018, The evolution, current status, and future prospects of using biotechnologies in the mineral extraction and metal recovery sectors: Minerals, v. 8, 343.

Kamradt, A., Borg, G., Schaefer, J., Kruse, S., Fiedler, M., Romm, P., Schippers, A., Gorny, R., du Bois, M., Bieligk, C., Liebetrau, N., Nell, S., Friedrich, B., Morgenroth, H., Wotruba, H., and Merkel, C., 2012, An integrated process for innovative extraction of metals from Kupferschiefer mine dumps, Germany: Chemie Ingenieur Technik, v. 84, p. 1694–1703.

Ketris, M. P., and Yudovich, Y. E., 2009, Estimations of Clarkes for carboniferous biolithes—world averages for trace element contents in black shales and coals: International Journal of Coal Geology, v. 78, p. 135–148.

Kim, J. S., Chung, K. W., Lee, H. I., Yoon, H.-S., and Kumar, J. R., 2014, Leaching behavior of uranium and vanadium using strong sulfuric acid from Korean black shale ore: Journal of Radioanalytical and Nuclear Chemistry, v. 299, p. 81–87.

King, H. M., 2021, REE—rare earth elements and their uses, Geoscience News and Information, Geology.com <https://geology.com/articles/rare-earth-elements>, accessed July 2025.

King, J. F., Taggart, R. K., Smith, R. C., Hower, J. C., and Hsu-Kim, H., 2018, Aqueous acid and alkaline extraction of rare earth elements from coal combustion ash: International Journal of Coal Geology, v. 195, p. 75–83.

Kolker, A., Scott, C., Hower, J. C., Vazquez, J. A., Lopano, C. L., and Dai, S., 2017, Distribution of rare earth elements in coal combustion fly ash, determined by SHRIMP-RG ion microprobe: International Journal of Coal Geology, v. 184, p.1–10.

Kolker, A., Scott, C., Lefticariu, L., Mastalerz, M., Drobniak, A., and Scott, A., 2021, Trace element partitioning during coal preparation—insights from U.S. Illinois Basin coals: International Journal of Coal Geology, v. 243, 103781.

Kumari, A., Parween, R., Chakravarty, S., Parmar, K., Pathak, D. D., Lee, J., and Jha, M. K., 2019, Novel approach to recover rare earth metals (REMs) from Indian coal bottom ash: Hydrometallurgy, v. 187, p. 1–7.

Kuppusamy, V. K., Kumar, A., and Holuszko, M., 2019, Simultaneous extraction of clean coal and rare earth elements from coal tailings using alkali-acid leaching process: Journal of Energy Resources Technology, v. 141, 070708.

Leventhal, J. S., 1993, Metals in black shales, in Engel, M. H., and Macko, S. A., eds., Organic Geochemistry: Plenum Press, New York, p. 581–592.

Lien, R.H., 1985, Recovery of lithium from a montmorillonite-type clay: Report of Investigations 896, U.S. Department of the Interior, Bureau of Mines, 16 p.

Lin, R., Stuckman, M., Howard, B. H., Bank, T. L., Roth, E. A., and Macala, M. K., 2018, Application of sequential extraction and hydrothermal treatment for characterization and enrichment of rare earth elements from coal fly ash: Fuel, v. 232, p. 124–133.

Mentani, T., 2010, So-called "Ion-adsorption type" REE deposits found in weathered crust of ilmenite-series granite in Northern Vietnam [abstract]: Geological Society of America Abstracts with Programs, v. 42, no. 5, p. 336.

Moldoveanu, G. A., and Papengelakis, V. G., 2016, An overview of rare-earth recovery by ion-exchange leaching from ion-adsorption clays of various origins: Mineralogical Magazine, v. 80, p. 63–76.

Montross, S. N., Yang, J., Britton, J., McKoy, M., and Verba, C., 2020, leaching of rare earth elements from Central Appalachian Coal Seam underclay: Minerals, v. 10, 577.

Munyan, A. C., 1938, Supplement to sedimentary kaolins of Georgia: Geological Survey of Georgia Bulletin, no. 44-A, 42 p.

Murakami, H., and Ishihara, S., 2008, REE mineralization of weathered crust and clay sediment on granitic rocks in the Sanyo Belt, SW Japan and the Southern Jiangxi Province, China: Resource Geology, v. 58, no. 4, p. 373–401.

Murty, Y. V., Alvin, M. A., and Lifton, J.P., 2024, Rare earth metals and minerals industries—status and prospects: Cham, Springer, 508 p.

Orberger, B., Delarue, V., Rodriguez, C., Salaün, A., Wallmach, T., Wirth, R., Boussafir, M., Dreux, G., Lafon, S., and Schreiber, A., 2018, In-situ analyses of carbonaceous matter in manganiferous black shales—analytical proxies and implication for ore processing: Minerals Engineering, v. 125, p. 83–93.

Ostrom, M. E., Hopkins, M. E., White, W. A., and McVicker, L. D., 1955, Uranium in Illinois black shales: Illinois Geological Survey Circular 203, 15 p.

Oxford Institute for Energy Studies, July 2023, China's rare earths dominance and policy responses, <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/06/CE7-Chinas-rare-earths-dominance-and-policy-responses.pdf>.

Pan, J., Nie, T., Vaziri Hassas, B., Rezaee, M., Wen, Z., and Zhou, C., 2020, Recovery of rare earth elements from coal fly ash by integrated physical separation and acid leaching: Chemosphere, v. 248, 126112.

Pan, J., Zhou, C., Tang, M., Cao, S., Liu, C., Zhang, N., Wen, M., Luo, Y., Hu, T., and Ji, W., 2019, Study on the modes of occurrence of rare earth elements in coal fly ash by statistics and a sequential chemical extraction procedure: Fuel, v. 237, p. 555–565.

Pan, J., Hassas, B. V., Rezaee, M., Zhou, C., and Pisupati, S. V., 2021, Recovery of rare earth elements from coal fly ash through sequential chemical roasting, water leaching, and acid leaching processes: Journal of Cleaner Production, v. 284, 124725.

Park, D. M., Brewer, A., Reed, D. W., Lammers, L. N., and Jiao, Y., 2017, Recovery of rare earth elements from low-grade feedstock leachates using engineered bacteria: Environmental Science & Technology, v. 51, no. 22, p. 13471–13480.

Peacor, D. R., Coveney, R. M., and Zhao, G., 2000, Authigenic illite and organic matter—the principal hosts of vanadium in the Mecca Quarry Shale at Velpen, Indiana: Clays and Clay Minerals, v. 48, no. 3, p. 311–316.

Peiravi, M., Dehghani, F., Ackah, L., Baharlouei, A., Godbold, J., Liu, J., Mohanty, M., and Ghosh, T., 2021, A review of rare-earth elements extraction with emphasis on non-conventional sources—coal and coal byproducts, iron ore tailings, apatite, and phosphate byproducts: Mining, Matallurgy, and Exploration, v. 38, p. 1–26.

Ramasamy, D. L., Puhakka, V., Iftekhar, S., Wojtuś, A., Repo, E., Ben Hammouda, S., Iakovleva, E., and Sillanpää, M., 2018, N- and O- ligand doped mesoporous silica-chitosan hybrid beads for the efficient, sustainable and selective recovery of rare earth elements (REE) from acid mine drainage (AMD)—understanding the significance of physical modification and conditioning of the polymer: Journal of Hazardous Materials, v. 348, p. 84–91.

Resources for the Future, 2025, The strategic game of rare earths: Why China may only be in favor of temporary export restrictions, <https://www.rff.org/publications/issue-briefs/the-strategic-game-of-rare-earths-why-china-may-only-be-in-favor-of-temporary-export-restrictions/>.

Reuters, July 17, 2025, China's tightest rare-earths headlock is financial, <https://www.reuters.com/commentary/breakingviews/chinas-tightest-rare-earths-headlock-is-financial-2025-07-17/>.

Reuters, August 8, 2025, US licenses Nvidia to export chips to China, <https://www.reuters.com/world/china/us-licenses-nvidia-export-chips-china-official-says-2025-08-08/?utm>.

Riekkola-Vanhanen, M., 2013, Talvivaara mining company—from a project to a mine: Minerals Engineering, v. 48, p. 2–9.

Ross, C. S. and Kerr, P. F., 1935, Halloysite and allophane: USGS Professional paper 185-G, p. 135–148.

Rozelle, P. L., Khadilkar, A. B., Pulati, N., Soundarrajan, N., Klima, M. S., Mosser, M. M., Miller, C. E., and Pisupati, S. V., 2016, A study on removal of rare earth elements from US coal byproducts by ion exchange: Matallurgical and Materials Transactions E, v. 3, p. 6–17.

Rudnick, E., 2024, Review on gallium in coal and coal waste materials—exploring strategies for hydrometallurgical metal recovery: Molecules, v. 29, 5919.

Rudnick, R. L., and Gao, S. 2014, Composition of the continental crust: Treatise on geochemistry, 2nd ed., v. 4, p. 1–51.

Runnels, R. T., Schleicher, J. A., and van Nortwick, H. S., 1953, Composition of some uranium-bearing phosphate nodules from Kansas shales: Kansas Geological Survey Bulletin, v. 102, p. 93–104.

Saikia, B. K., Hower, J. C., Islam, N., Sharma, A., and Das, P., 2021, Geochemistry and petrology of coal and coal fly ash from a thermal power plant in India: Fuel, v. 291, 120122.

Sandell-Hay, 2022, South Australian kaolin miners unveil significant REE potential, <https://www.theassay.com/articles/analysis/south-australian-kaolin-miners-unveil-significant-ree-potential/>, accessed July 2025.

Silva, L. F. O., DaBoit, K., Sampaio, C. H., Jasper, A., Andrade, M. L., Kostova, I. J., Waanders, F. B., Henke, K., R., and Hower, J. C., 2012, The occurrence of hazardous volatile elements and nanoparticles in Bulgarian coal fly ashes and the effect on human health exposure: Science of Total Environment, v. 416, p. 513–526.

Schultz, R. B., 1991, Metalliferous black shales—accumulation of carbon and metals in cratonic basins, in Force, E. R., Eidel, J. J., Maynard, J. B., Robertson, J. M., eds., Sedimentary and diagenetic mineral deposits—a basin analysis approach to exploration: Reviews in Economic Geology, v. 5, p. 171–176.

Seredin, V. V., 2004, Metalliferous coals—formation conditions and outlooks for development, in Coal Resources of Russia, v. VI. Geoinformmark, Moscow, p. 452–519 (in Russian).

Seredin, 2010, A new method for primary evaluation of the outlook for rare earth element ores: Geology of Ore Deposits, v. 52, p. 428–433.

Seredin, V. V., and Dai, S., 2012, Coal deposits as potential alternative sources for lantanides and yttrium: International Journal of Coal Geology, v. 94, p. 67–93.

Sverdrup, H. U., Ragnarsdottir, K. V., and Koca, D., 2017, An assessment of metal supply sustainability as an input to policy—security of supply extraction rates, stock-in-use, recycling, and risk of scarcity: Journal of Cleaner Production, v.140, p. 359–372.

Swanson, V. E., 1961, Geology and geochemistry of uranium in marine black shales—a review: U.S. Geological Survey Professional Paper 356-C, 46 p.

Taggart, R. K., Hower, J. C., Dwyer, G. S., and Hsu-Kim, H., 2016, Trends in the rare earth element content of U.S. based coal combustion fly ashes: Environmental Science & Technology, v. 50, p. 5,919–5,926.

Taggart, R.K., Hower, J.C., Hsu-Kim, H., 2018, Effects of rosting additives and leaching parameters on the extraction of rare earth elements from coal fly ash: International Journal of Coal Geolog,y 196, 106-114.

Tang, Y., 2023, Hidden gems—hunting rare earth elements in Georgia kaolins, Georgia Tech College of Sciences, <https://cos.gatech.edu/news/hidden-gems-hunting-rare-earth-elements-georgia-kaolins>, accessed July 2025.

Thomas, B. S., Dimitriadis, P., Kundu, C., Vuppaladadiyam, S. S. V., Singh Raman, R. K., and Bhattacharya, S., 2024, Extraction and separation of rare earth elements from coal and coal fly ash—a review on fundamental understanding and on-going engineering advancements: Journal of Environmental Chemical Engineering, v. 12, 112769.

Time, June 17 2025, Trump wants rare earths. But challenging China's dominance will take more than tariffs, <https://time.com/7294964/us-rare-earths-minerals-china-dominance-trump-tariffs/>.

Tissot B. P., and Welte, D. H., 1984, Petroleum formation and occurrence, 2nd ed.: Springer-Verlag, Berlin, 699 p.

Tourtelot, H. A., and Brenner-Tourtelot, E. F., 1977, Lithium in flint clay, bauxite, related high-alumina materials and associated sedimentary rocks in the United States—a preliminary survey: USGS Open-File Report 77-786, 46 p.

U.S. Geological Survey (USGS), 2022a, U.S. Geological Survey releases 2022 list of critical minerals, U.S. Geological Survey, <https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals>, accessed July 2025.

U.S. Geological Survey (USGS), 2022b, Mineral commodity summaries 2022: U.S. Geological Survey, p. 64–65.

U.S. Geological Survey (USGS), 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, 212 p.

U.S. Department of Energy, 2017, Report on rare earth elements from coal and coal byproducts: Report to Congress, January 2017, 43 p.

U.S. Department of Energy, 2022, Recovery of rare earth elements and critical materials from coal and coal byproducts: Report to Congress, May 2022, 85 p.

U.S. Department of Energy, 2025, What are critical materials and critical minerals?, <https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals>, accessed July 2025.

Vass, C. R., Noble, A., and Ziemkiewicz, P. F., 2019, The occurrence and concentration of rare earth elements in acid mine drainage and treatment by-products—part 1, initial survey of the Northern Appalachian Coal Basin: Mining, Metallurgy, and Exploration, v. 36, no. 5, p. 903–916.

Vind, J., and Tamm, K., 2021, Review of the extraction of key metallic values from black shales in relation to their geological and mineralogical properties: Minerals Engineering, v. 174, 107271.

Wang, Z., Dai, S., Zou, J., French, D., and Graham, I. T., 2019, Rare earth elements and yttrium in coal ash from the Luzhou power plant in Sichuan, Southwest China—concentration, characterization, and optimized extraction: International Journal of Coal Geology, v. 203, p. 1–14.

Wen, Z., Zhou, C., Pan, J., Cao, S., Hu, T., and Ji, W., 2020, Recovery of rare-earth elements from coal fly ash via enhanced leaching. Int J Coal Prep Util 2020, 1-15.

Wenger, L. M., and Baker, D. R., 1986, Variations in organic geochemistry of anoxic-oxic black shale carbonate sequences in the Pennsylvanian of the Midcontinent, U.S.A.: Organic Geochemistry, v. 10, no. 1–3, p. 85–92.

World Integrated Trade Solution, 2023, United States rare-earth metals, scandium and yttrium imports by country in 2023, <https://wits.worldbank.org/trade/comtrade/en/country/USA/year/2023/tradeflow/Imports/partner/ALL/product/280530?utm>.

Wu, L., Zhang, J., Huang, Z., Zhang, Y., Xie, F., Zhang, S., and Fan, H., 2023, Extraction of lithium as lithium phosphate from bauxite mine tailings via mixed acid leaching and chemical precipitation: Ore geology Reviews, v. 160, 105621.

Xie, Y., Hou, Z., Goldfarb, R.J., Guo, X., and Wang, L., 2016, Rare earth element deposits in China, in Verplanck, P. L., and Hitzman, M. W., eds., Reviews in economic geology, v. 18, p. 115-136.

Yang, J., Montross, S., Britton, J., Stuckman, M., Lopano, C., and Verba, C., 2020, Microanalytical approaches to characterizing REE in Appalachian Basin underclays: Minerals, v. 10, 546.

Zhang, W., and Honaker, R., 2018, Rare earth elements recovery using staged precipitation from leachate generated from coarse coal refuse: International Journal of Coal Geology, v. 195, p.189–199.

Zhang, W., and Honaker, R. 2019, Enhanced leachability of rare earth elements from calcined products of bituminous coals: Minerals Engineering, v. 142, 105935.

Zhang, W., and Honaker, R., 2020a, Process development for the recovery of rare earth elements and critical metals from an acid mine leachate: Minerals Engineering, v. 153, 106382.

Zhang, W., and Honaker, R., 2020b, Characterization and recovery of rare earth elements and other critical metals (Co, Cr, Li, Mn, Sr, and V) from the calcination products of a coal refuse sample: Fuel, v. 267, 17236.

Zhang, W., Noble, A., Yang, X., and Honaker, R., 2020a, A comprehensive review of rare earth elements recovery from coal-related materials: Minerals, v. 10, 451.

Zhang, W., Noble, A., Yang, X., and Honaker, R., 2020b, Lithium leaching recovery and mechanisms from density fractions of an Illinois Basin bituminous coal: Fuel, v. 268, 117319.

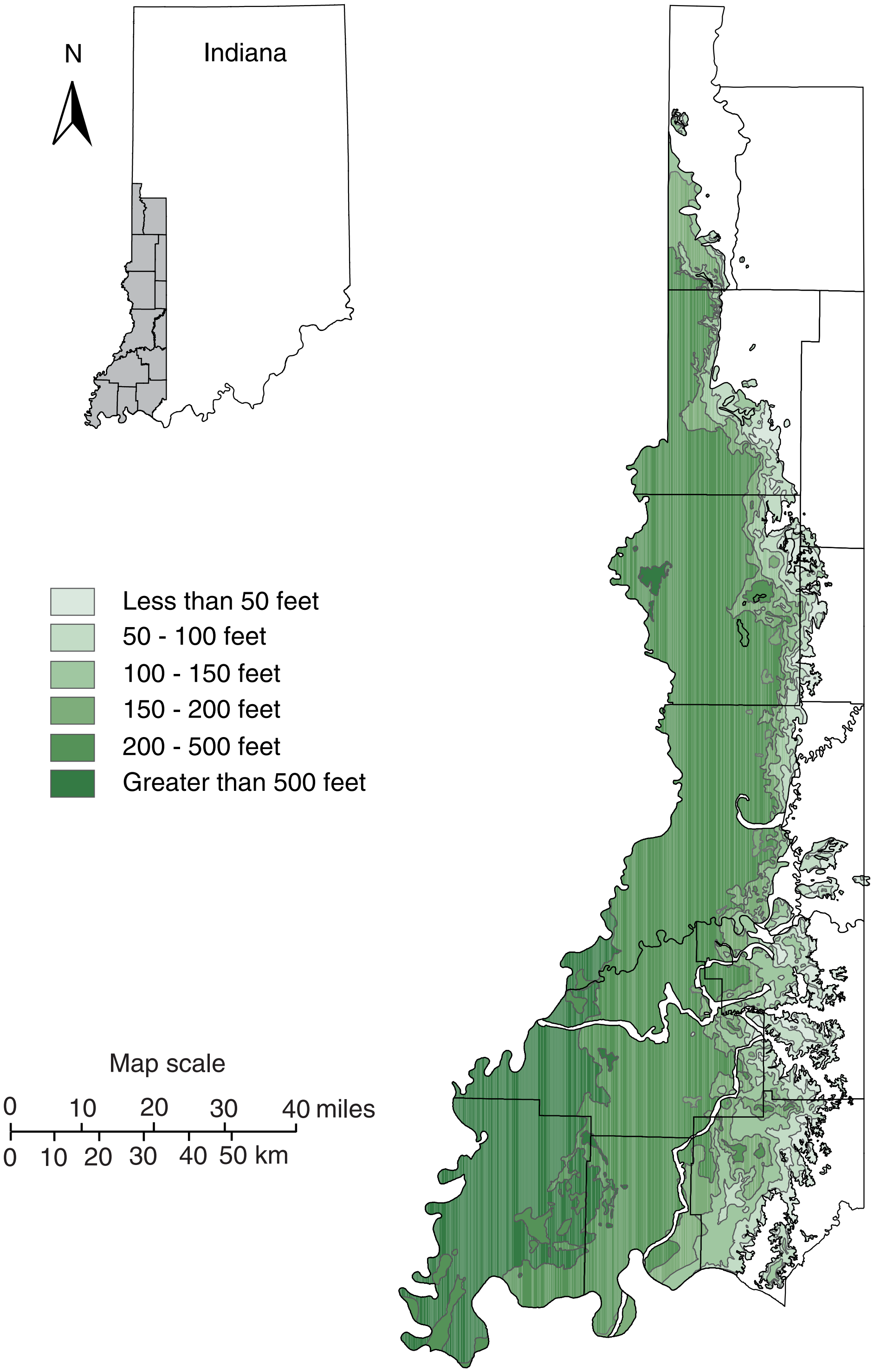
Zou, J., Tian, H., and Wang, Z., 2017, Leaching process of rare earth elements, gallium and niobium in a coal-bearing strata-hosted rare metal deposit—a case study from the Late Permian tuff in the Zhongliangshan Mine, Chongqing: Metals, v. 7, 174.

Ziemkiewicz, P., 2019, Recovery of rare earth elements (REEs) from coal mine drainage, phase 2: Project Summary Report, DOE Award DE-FE0026927, 86 p.

Ziemkiewicz, P., and Noble, A., 2019, Recovery of rare earth elements (REEs) from coal mine drainage, NETL REE Review Meeting: Pittsburgh, Pa., USA.

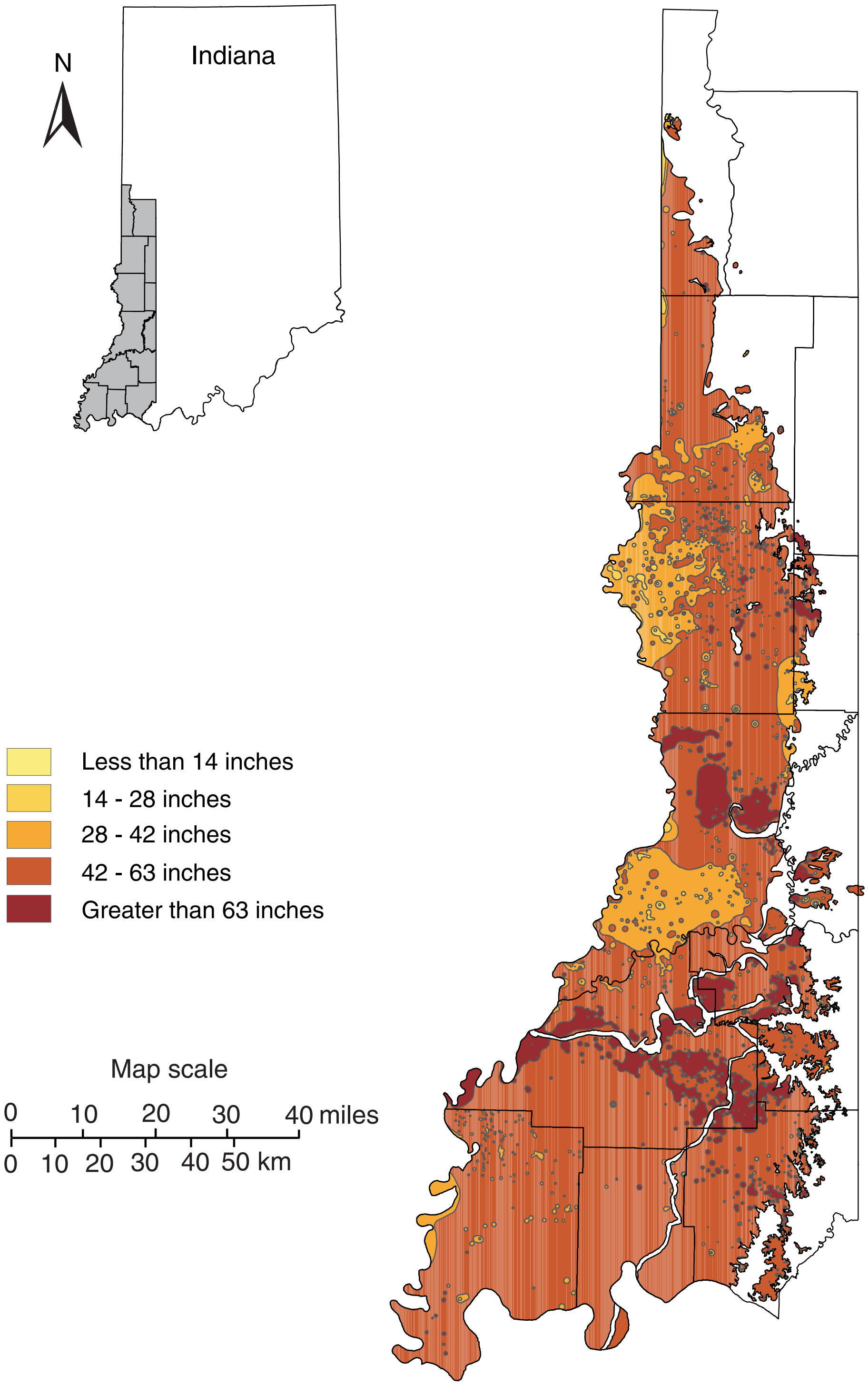
APPENDIX 1

Structure contour (depth) map of southwestern Indiana showing the depth of the Springfield Coal Member.



APPENDIX 2

Isopach (thickness) map of southwestern Indiana showing the thickness of the Springfield Coal Member.



APPENDIX 3

Companies in Indiana involved in research or recovery of REEs.

Institution	Contact	Technique	Result
Purdue University, School of Chemical Engineering, West Lafayette	Prof. L. Wang https://engineering.purdue.edu/WangLab 480 Stadium Mall Drive, West Lafayette, IN 47907 (765) 494-4050	Ligand-assisted chromatography method	Separation of Dy, Nd, and Pr from used magnets
Recycle Force, Indianapolis	Daniel Rove https://recycleforce.org/ 816 N Sherman Drive, Indianapolis, IN 46201 (317) 532-1367	Acid-free dissolution recycling (DOE-funded project)	REE oxides from magnets
ReElement Technologies LLC, Noblesville site. They are constructing a commercial facility in Marion to be completed early 2026.	https://www.reelementtech.com/ (317) 855-9926 Headquarters: 12115 Visionary Way, suite 174, Fishers, IN 46038 JTC Team, LLC, Jenene Thomas, at (833) 475-8247 or arec@jtcir.com	Utilize high-value Purdue-patented technologies based on ligand-assisted chromatography	Production of isolated and purified rare earth elements from ore concentrates and recycled magnets. Focus on high-purity Y, Ga, Sa, Tb but also Ga and Ge. Plans call for producing up to 4,400 metric tons per year.
Indiana Geological and Water Survey (IGWS), Indiana University	https://igws.iu.edu/	Mapping and evaluating potential sources for REE-CM	REE-CM data on coal, coal waste, coal ash, paleosols and shales

APPENDIX 4

Other projects, companies, and contacts related to REEs in the USA.

The Mountain Pass Mine, California https://mpmaterials.com/ 702 844-6111	It is the largest and only producing rare earth element mine (pen pit) in the United States. Discovered in 1949 by prospectors searching for uranium, it sits on a rich Precambrian carbonatite formation that contains high-grade deposits of rare earths, especially neodymium. As of 2022, work was done to restore processing capabilities both for light and heavy REEs to alleviate supply chain risk. The mine was reported as operating in 2025. MP Materials, operator of the Mountain Pass Mine has received multi-billion-dollar support from the Department of Defense, including a $400 million equity investment, a $150 million loan to expand heavy rare earth separation capacity, and 10-year agreements guaranteeing magnet purchases and minimum prices for key oxides.
Ramaco Brook Mine, Wyoming Ramaco Resources https://ramacoresources.com/critical-minerals/	Opened in Wyoming in 2005, the mine produces coal, with plans to include a processing plant to recover REEs.
Halleck Creek deposit, Wyoming America Rare Earth (ARR)	Estimated at 2.6 billion tons of high-grade REEs, this deposit is in the permitting and test mining phase. The primary rock types are clinopyroxene quartz monzonite and biotite hornblende syenite.
Vacuumschmelze (VAC) https://vacuumschmelze.com/shared/quicknav/contact	According to recent reports, the German company Vacuumschmelze (VAC) is expanding its rare earth magnet production in the United States rather than exploring for rare earth minerals. Backed by the U.S. government, VAC is building a magnet manufacturing plant in South Carolina to help reduce reliance on China for rare earth magnets. The company is owned by the American private equity firm Ara Partners, which focuses on industrial decarbonization and acquired VAC in October 2023 from Apollo Global Management. A leading magnet producer outside China, VAC is transferring its technology from Germany to the new South Carolina facility, expected to open before the end of 2025. The plant will supply magnets for electric vehicles, wind turbines, and defense applications. The U.S. government is providing extensive support through funding and tax incentives—aid that the company says exceeds what is available in Europe. This expansion is part of a broader Western effort to build independent rare earth supply chains. Although VAC is now manufacturing magnets in the U.S., it has historically sourced its feedstock from outside China through long-term offtake agreements.
Lynas USA https://lynasrareearths.com/	Lynas USA has been awarded more than $150 million from the Department of Defense to establish commercial-scale rare earth oxide production in the United States.
E-VAC Magnetics https://www.evacmagnetics.com/	E-VAC Magnetics, which is developing a magnet manufacturing plant in South Carolina, received $94 million in Department of Defense funding and $112 million in tax credits under the Inflation Reduction Act.

APPENDIX 5

List of acronyms used in this report.

Acronym	Explanation
AMD	Acid mine drainage
AML	Abandoned mine lands
CCR	Coal combustion residuals
CM	Critical minerals
DES	Deep eutectic solvents
ELG	Effluent Limitation Guidelines Rule
IDEM	Indiana Department of Environmental Management
IDNR	Indiana Department of Natural Resources
IGWS	Indiana Geological and Water Survey
DOE	Department of Energy
HREE	Heavy rare earth elements
IL	Ionic liquids
LREE	Light rare earth elements
NPDES	National Pollution Discharge Elimination System
PLS	Pregnant leach solution
RCRA	Resource Conservation and Recovery Act
REE	Rare earth elements
SMCRA	Surface Mining Control and Reclamation Act
SRB	Sulfate reducing bioreactors
SX	Solvent extraction
USGS	United States Geological Survey
VFP	Vertical flow ponds