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Assessment of Rare Earth Element Potential in Gulf Coast Coals and Coal Ash

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Abstract

United States heavy reliance on imports of critical minerals (CMs), including rare earth elements (REEs), underscores the importance of development of domestic sources. The study objective was to quantify CM and REE concentrations in coals in the US Gulf Coast region. CM and REE concentrations were measured for 118 samples from outcrops and 14 mines in the Gulf Coast. Results show that total REE+Yttrium (REY) concentrations (dry coal basis) are comparable to those of the upper continental crust (UCC) with localized hot spots, such as the Texas Gibbons Creek mine ($\text{REY} \leq \sim 2,860$ ppm). When normalized to UCC REY concentration (169 ppm, dry coal basis), REY to UCC ratios for Gulf Coast coal samples range from 2.2 to 307 (median ratio 11). REE extractability from lignites is high (median: 63–93%) using environmentally benign weak acid. In addition to raw coal, coal ash from power plants could also serve as a REE source with median REY concentration ~ 3 times higher than that from coal; however, extractability from coal ash is generally much lower (~ 20 – 30%). The median price for extracted REY + scandium (Sc) is $\sim \$10/\text{tonne}$ of coal assuming $\sim 50\%$ extraction. Although estimated Gulf Coast coal resources are high (10s of billions of tonnes), there are only five active coal mines that produced ~ 15 million tonnes in 2023. Estimated power plant coal ash volume in landfills/ponds and potentially accessible is ~ 260 million tonnes. REE production from coal would likely require co-products, such as activated carbon or humic acids, to attain economic viability. Production of REEs from coal ash could offset remediation costs related to potential water contamination. This reconnaissance study shows the potential for REE production from coal and coal ash in the Gulf Coast; however, carbon coproducts and/or societal benefits would likely be required for socioeconomic viability.

1.0 Introduction

Critical minerals (CMs), including rare earth elements (REEs), are important for economic growth, national security, and technological advances in the United States (U.S.) and globally¹. Minerals are defined as critical if they are important for specialized applications but at risk of supply disruption. The most recent compilation of critical minerals by the U.S. Geological Survey (USGS) encompasses 50 elements, including 14 REEs and 36 other elements/minerals (Table S1)². The REE group includes 15 elements from lanthanum (La, atomic no. 57) through lutetium (Lu, atomic number 71), commonly termed the lanthanides. Promethium (Pm, atomic no. 61) is one of the 15 REEs/lanthanides but is not considered a CM. Additionally, yttrium (Y, atomic number 39) and scandium (Sc, atomic number 21) are generally considered REEs because of similarities in physical and chemical properties and general co-occurrence

with REEs³. Owing to their unique geochemical behavior and/or characteristics, REEs are considered non-substitutable, making their supply chains particularly vulnerable to interruptions. Currently, the U.S. and other nations are heavily reliant on REE imports from China. For example, in the U.S., REE compound and metal imports from China accounted for 75% of all imported REEs from 2018 through 2021⁴. China also dominates in terms of REE production and processing, accounting for ~70% of global production and ~85% of the global processing totals¹.

The unique magnetic, phosphorescent, and catalytic properties of REEs result in their widespread use in a variety of modern technologies (Table S1b), including smartphones, computers, electric vehicles, renewable energy technologies, military applications, and other advanced technologies^{5,6}. Praseodymium (Pr), neodymium (Nd), terbium (Tb) and dysprosium (Dy) are widely used in permanent magnets deployed in wind turbines, electric vehicles, and smartphones^{1,7}. Yttrium and Tb are used for phosphors in cathode ray tube monitors, fluorescent lamps, and liquid crystal displays in computer monitors and smartphones⁸. Several REEs are used in solid state lasers, e.g., Nd, erbium (Er), holmium (Ho), and thulium (Tm)⁵. Future demand for REEs is projected to increase substantially under various climate-driven scenarios⁹.

The U.S. Department of Energy (DOE) recently released a global critical materials assessment with future projections, discussing ‘levels of criticality’ based on an element’s importance for energy development and supply chain risks¹⁰. Their analysis shows that Nd, Tb, and Dy are considered critical in the short term (2020 to 2025), whereas Pr is considered as ‘near critical’. The medium-term analysis ranks all of these elements as critical. Nd-Fe-B magnets are important for wind turbines and electric vehicles and Pr and Tb are added to improve operation performance at high temperatures¹¹. To mitigate potential supply disruptions through source diversification, the U.S. DOE has developed programs to increase domestic production of CMs and REEs¹².

Although REEs are not actually rare in terms of their abundance in the Earth’s crust¹³, they are not typically found in concentrated deposits, making their extraction and production technically challenging and cost-prohibitive. Traditionally, REEs in the U.S. have been extracted from conventional sources, such as from the minerals bastnäsite and monazite in carbonatites in deposits at Mountain Pass (California)¹⁴; similar deposits have been identified at Bear Lodge (Wyoming)¹⁵ and at Lemhi Pass (Montana-Idaho border)¹⁶. Mountain Pass was a major producer of REEs in the 1980s and 1990s but closed in response to environmental concerns. However, Mountain Pass Materials acquired Mountain Pass in 2017 and produced 41,600 tonnes of rare earth oxide concentrate and 200 tonnes of NdPr oxide in 2023¹⁷ (1.00 tonne (metric) = 1.10 U.S. ton, Imperial unit). Placer deposits represent another domestic REE source, with paleoshoreline sands of the Atlantic Coastal Plain in Florida and Georgia producing REEs from detrital

monazite^{16,18}. In addition to these conventional REE sources, the U.S. is also evaluating the potential to develop REEs from unconventional sources, such as mine tailings¹⁹, geothermal brines²⁰, industrial waste and byproducts²¹, and coal and coal byproducts^{22,23}.

REE extraction from coal and coal byproducts shows promise to increase domestic production of REEs as many countries that rely on REE imports have substantial coal resources. The U.S. DOE has initiated a program titled Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) to evaluate coal from mines and coal byproducts (e.g., coals ash at power plants) as potential sources of REEs in 13 regions throughout the U.S.²³. The mission of the CORE-CM program is to develop an economic, competitive, and sustainable domestic REE-CM supply to support the clean energy transition and economic and national security.

A comprehensive coal resource assessment of ~60 coal beds in the U.S. indicates that over 1.5 trillion tonnes (Tt) of coal remain in the U.S.²⁴, including ~88 billion tonnes in the upper ~150 m (~500 ft) in the southeastern U.S. Gulf Coastal Plain (Gulf Coast) region²⁵. The U.S. coals vary in rank from lignite, primarily in the Gulf Coast region and the Williston Basin, to subbituminous coals in the Powder River Basin and the Rocky Mountain Region, and bituminous coals in the Appalachian and interior U.S. basins²⁶. Limited studies to date indicate variable concentrations of REEs in U.S. coal. For example, total REE + Yttrium (REY) concentrations range from 250 to 4,100 ppm (=mg/kg, ash basis) in central Appalachian coals, including the Fire Clay coals²⁷. Localized enrichment of REEs have also been found in North Dakota (up to 2,600 ppm REY, dry coal basis), up to 14 times the estimated concentrations in the upper continental crust (UCC, Table S1a)^{13,28}.

In addition to REE concentrations, extractability is also a critical issue both from economic and environmental perspectives. Previous studies indicate that REEs in lignites from North Dakota are more readily extractable using environmentally benign acids because the REEs occur in the organic phase in these low-rank lignites rather than in phosphates or silicates, as in more mature subbituminous to bituminous coals^{29,30}.

The primary objective of this study was to quantify the concentrations of REEs and other CMs in coal from the Gulf Coast region and assess their potential as a domestic REE supply source. The analysis also considered REEs from coal from mines versus coal combustion ash from power plants. The Gulf Coast region provides a well-constrained case study because of detailed geological data that are available for this region related to its long history of resource assessment and development (e.g., oil, gas, coal, aggregate minerals, and water)^{25,31,32,33,34,35}. Further, potential future REE and CM processing facilities in the Gulf Coast region could benefit from the existing well-developed industrial infrastructure (including

roads and railways) because 48% of the U.S. petroleum refining capacity and 51% of the U.S. natural gas processing plant capacity is located along the Gulf Coast³⁶.

2.0 Materials and Methods

All data are provided in the Supporting Information, including sample locations (Table S2), REY and CM concentrations on a dry coal basis (Table S3) with ratios relative to UCC (Table S4), and a correlation matrix for REEs and CMs (Table S5), REY and CM concentrations on an ash basis (Table S6) with ratios relative to UCC (Table S7), REE concentrations in coal and coal partings (Table S8), extractability of REEs (Table S9), mean annual prices of REOs (Table S10), rare earth oxide (REO) concentrations on a dry coal basis along with prices (Table S11), REO on an ash basis (Table S12), coal production in the Gulf Coast (Table S13), status of coal mines (Table S14), source of coal for power plants in Gulf Coast (Fig. S1, Table S15), and electricity generation by fuel source (Table S16).

2.1 Samples

Critical mineral compositional data, including REEs, were collated for 118 samples that were taken from outcrops, coal mines, and public databases (Table S2). The majority of samples (n=63) were collected by the USGS in the 1990s and 2000s, archived at USGS headquarters in Reston, Virginia (U.S.), and made available for compositional analysis for this study. The USGS samples represent 13 coal mines, with 10 mines in Texas, two mines in Louisiana (Dolet Hills and Oxbow), and one mine in Mississippi (Red Hills); and coal outcrops in an abandoned mine in Arkansas (Camden) and two clay pits in Tennessee and Kentucky (Swaim and Sims) (Fig. 1). In addition to the archived USGS samples, new samples were collected from the active San Miguel mine in Texas (n=6) and from coal outcrops in Alabama (n=12) and Arkansas (n=3). The analytical data collected for this study were complemented by publicly available data (n=34) from Zygarlicke et al. (2019)³⁸ and accessed through the U.S. DOE Data eXchange (EDX) database.

2.2 Rare Earth Element and Critical Mineral Analyses

Details of sample processing are provided in Supporting Information (SI), Section 1. Samples (84) were analyzed for their elemental composition by Standard Laboratories, Inc. (Freeburg, Illinois, U.S.). All samples were analyzed for REE + Y + Sc and 23 other CMs as well as U (Tables S3, S6). Quantitative elemental analysis was performed following ASTM (2021) D6357 using Method B for Inductively Coupled Plasma Mass Spectrometry (ICP-MS) determination³⁹. All REE data are reported on a dry coal basis (Table S3a,b) and on an ash basis by dividing by the ash percentage in each sample (Table S6). Basic analytical data, including moisture, ash yield, sulfur, calorific value, oxide, from most coal samples used in this study

were previously reported^{40,41,42,43} and elemental data are available through the USGS Energy Resources Program (2014)⁴³ (Table S3c).

2.3 Rare Earth Element Extraction

The extractability of REEs from coal was evaluated in five samples using general sequential extraction procedures (SI, Section 2)³⁰. One sample was selected from the Gibbons Creek archive because of high REE concentrations⁴⁴ and four samples from San Miguel mine, which were collected during this study. Extractions were conducted at the University of North Dakota, Institute of Energy Studies. Sequential extraction was conducted using water initially, then ammonium acetate to quantify ion exchangeable REE concentrations, and a weak acid (0.5 molar HCl). The kinetics were rapid, generally less than 2 to 3 h to reach equilibrium. REE concentrations in the residues were analyzed at Standard Laboratories using the same procedure as for the coal analyses.

3.0 Results

3.1 Distribution of Rare Earth Elements in Gulf Coast Coals

Total REY concentrations in the Gulf Coast region vary from ~18 to 2862 ppm on a dry coal basis (n=118 samples) (Fig. 2, Tables 1, S3a). The data are right skewed because the mean (178 ppm) is much higher than the median (109 ppm, Fig. S2) probably because only 10% (12/118 samples) have REY concentrations exceeding 300 ppm, mostly restricted to the Gibbons Creek mine (eight samples) and single samples from Alabama and Arkansas (Table S3a). The Gibbons Creek samples have elevated REY concentrations likely because of the influence of leached volcanic ash⁴⁴; it is uncertain why samples from Alabama and Arkansas have elevated concentrations. Some studies include Sc with the total REE concentrations²⁷ even though Sc concentration trends differ from the other REEs. Inclusion of Sc (1-25 ppm, n=118) into REY contents increases mean and median values by ~5%.

The highest REY concentrations were found in the Gibbons Creek mine (n=15, 48 to 2,862 ppm, mean 606 ppm, median 319 ppm; dry coal basis). Coals from the San Miguel mine, that was extensively sampled for this study (n=33), have lower REY concentrations and a narrower range between 73 and 209 ppm (mean=124 ppm, median, 119 ppm, dry coal basis). Approximately 25% of the samples have ash yields >50%, which indicates that they are not coals⁴⁵. In the Gulf Coast region, REEs are found mostly in the coals rather than in the partings (Fig. S3) and REY concentrations are generally not related to ash content (Fig. S4).

In addition to total abundances, REE concentrations in coal are generally reported relative to REE concentrations in the upper continental crust (UCC) (Table S1a)¹³. When normalized to REY concentration

in the UCC (169 ppm, dry coal basis), REY to UCC ratios for different coal samples range from 2.2 to 307 (mean ratio 18, median ratio 11, dry coal basis) (Fig. 3, Table S4a). Mean REE to UCC ratios for individual elements range from 0.9 to 1.4 (mean) and 0.5 to 0.9 (median) with slightly higher ratios for heavy REEs. Concentrations of Sc are notably lower than the composition of the UCC (mean=0.5, median=0.4).

Critical REE concentrations for clean energy (i.e., Pr, Nd, Tb, Dy) in the Gulf Coast are similar to UCC concentrations, but median values are about 0.6 to 0.7 relative to UCC (Fig. 3). The percentage of the sum of Pr, Nd, Tb, Dy for clean energy relative to REY (median 22%) is similar to that in the UCC (23%; Table S3). All of the REEs +Y are highly correlated with each other ($R > \sim 0.95$) with the exception of Sc with R values for Sc relative to the other 16 REEs ranging from 0.44 to 0.62 (Table S5).

3.2 Other Critical Minerals

In addition to REEs (+Y, Sc), 22 other critical minerals or elements were analyzed, as well as uranium (U) which is considered critical by the U.S. DOE⁴⁶ (Fig. S5, Table S3b). Elements with the highest enrichments relative to the composition of the UCC are Mg, Al, Ti, and Mn with median ratios ranging from 1,300 (Mn) to 3,300 (Ti) (Fig. 4). Other critical minerals with slight enrichments are Ge (median ratio of 2.1 and ratios up to 20 in Gibbons Creek mine, and Sb (with a median ratio 2.0 and ratios of up to 23 in the Oxbow mine and 5.6 in San Miguel mine). Uranium is slightly elevated relative to the composition of the UCC with a median ratio of 1.1 and ratios of up to 13 at Gibbons Creek mine.

3.3 Extractability of Rare Earth Elements

In addition to REE abundances, their extractability from different source materials is an important factor for REE development potential. Rare earth elements and Y and Sc from Gulf Coast lignites were readily extractable using environmentally benign, weak acid (0.5 molar HCl) with extraction percentages for individual REEs ranging from 53 to 96% (Fig. 5). No systematic variation in extractability of individual REEs or Y or Sc was found. REEs + Y and Sc were generally not water soluble and percentages that were extractable using ion exchange in ammonium acetate were mostly $\leq 6\%$ (Fig. S6). Most of the REEs were extracted using weak acid leaching. Extraction of ash during this process was generally low, mostly $\sim 30\%$. The extraction rates are similar to extraction rates of REEs reported for lignites in the Williston Basin in North Dakota³⁰ and are interpreted to reflect REE occurrence in organic rather than inorganic phases in the lignites (Fig. S4). Conversely, extraction of REEs from coal ash is generally lower⁴⁷ and often requires much stronger acids (e.g., 12 M HCl and 15 M HNO₃)⁴⁸. Limited studies of REE extractability from ashes derived from lignites in North Dakota indicate lower extractability for most samples (20 to 30%) with stronger acids (≤ 2 molar HCL)⁴⁹.

4.0 Discussion

4.1 Economic Analysis

Prices of REE have been variable over time, spiking in 2011 related to China's export restrictions from 2010 to 2011⁵⁰ and mostly decreasing in recent years possibly due to the implementation of environmental mining policies and industrial standards in China and increased production of REEs in other countries⁵¹ (Fig. S7, Table S10). Prices for Sc and Lu were highest (\$770 - \$820/kg, 2024) but are not widely used. Prices for Tb (\$790/kg) and Dy (\$260/kg) were also high and these elements are widely used for permanent magnets. Prices for the other REE magnet elements (Pr and Nd) were much lower (\$50/kg). Using data from 2024 as a conservative estimate for the economic value of REEs from Gulf Coast coals (i.e., REYSc = \$2,931 per kg, oxides; Table S10), and converting elemental REYSc to their oxides on a dry coal basis (24 to 3,411 ppm, median 137 ppm; Table S11a), yields price estimates of \$2.38 to \$173 per tonne of coal (median = \$14). These estimates assume 100% extractability for REEs; however, pilot testing for lignites in North Dakota suggest ~ 50% extractability at larger scales⁵¹. For context, the price for lignite at the time of writing was \$20/tonne (EIA, 2024).

The absolute value of the coal on an ash basis studied here is greater than the reported dry coal basis concentrations owing to the higher REYSc concentrations in the ash samples, giving price estimates \$6.54 to \$467 REYSc per tonne of ash (median = \$49; Table S12b). Sc contributes substantially to the median price, accounting for ~ 70% of the REYSc median price (note that the median price for REY, \$14.19, is about 70 percent lower than for REYSc, \$49.20, Table S12b). Assuming 50% extractability at larger scale would halve these prices. The greater REYSc value of the ash samples relative to dry coal does not necessarily imply that they represent a more economically viable resource as REE extraction from ash is lower and more complicated compared to that from coal.

In addition to quantitative REE abundances, the economic potential of a REE resource is often evaluated based on the ratio of heavy REEs (HREEs) to light REEs (LREEs) because HREEs are considered more valuable for various applications and HREE-rich deposits are rarer overall⁵². In the Gulf Coast coal samples studied here, HREEs are less abundant than LREEs (median ratio 0.4; Table S3). Some studies report HREE/LREE ratios after normalizing the data to UCC^{52,53}; however, dividing by the UCC, which has a HREE/LREE ratio of 0.3, artificially increases the median HREE/LREE ratio by ~6 times; in this study, for example, from 0.42 to 2.7 in the Gulf Coast samples (Tables S3, S4) which skews the data towards a theoretical economic value that is not representative of the quantitative elemental abundances. Moreover, some LREEs, such as Nd and Pr, are now considered among the most critical REEs for clean

energy applications which further emphasizes that HREE/LREE ratios are not necessarily useful measures for REE resource evaluations.

An alternative approach to evaluating REE resources was proposed by Seredin and Dai (2012)⁵⁴ who developed an outlook coefficient that considers the market value of different REEs and the ratio of critical REE to those that were considered excessive in stock at that time. The outlook coefficient (C_{outl}) is described as:

$$C_{outl} = (Nd+Eu+Tb+Dy+Er+Y/\sum REY)/(Ce+Ho+Tm+Yb+Lu/\sum REY) \quad (1)$$

with Nd, Eu, Tb, Dy, Er and Y being classified as critical REE, Ce, Ho, Tm, Yb, and Lu being classified as REE excessive in stock, and $\sum REY$ being the total of all REE+Y. Consequently, higher values of C_{outl} reflect greater potential for industrial development based on prices of REE at that time. In this scenario, coal resources with C_{outl} values > 0.7 are considered “promising” and those exceeding C_{outl} values of 1.9 “highly promising”^{52,53,54}. Out of the 118 coal samples studied here, 111 samples have C_{outl} values between 0.7 and 1.9, and three samples are greater than 1.9 (Fig. S8). Consequently, it can be argued that, based on the outlook coefficient of Seredin and Dai⁵⁴, most Gulf Coast coals represent a “promising” REE resource.

4.2 Considerations of Coal versus Coal Ash as a Source of REE in the Gulf Coast

There are many tradeoffs when considering coal from mines versus coal ash from power plants as a source of REEs (Table 2). Approximately 1,740 million tonnes of coal were produced in the Gulf Coast (1983 to 2022; Table S13). The median concentrations of REY in coal ash (354 ppm, dry coal basis) is ~3 times greater than that in dry coal (median=109 ppm) (Fig. 6) because REEs are nonvolatile and thus concentrated in the ash after combustion. However, extractability of REEs is much higher for coal (60 to 90%) (Fig. 5) relative to coal combustion ash and can be achieved through rather simple and environmentally benign sequential extraction with weak acid leaching^{29,30}. Therefore, REE extractability may partially counterbalance REE concentration differences between coal and ash and profitability considerations will need to be made on a case-by-case basis.

Another factor controlling the economic potential of coal vs. coal ash for REE extraction is the accessibility of materials for processing. The high cost of mining and coal beneficiation for REE production suggests that REE production would be most feasible in active mines where many of these costs would be absorbed by current production. Because REE levels are in the ppm range, if coal was produced for REE production alone, > 99% of the coal would remain after REE extraction and preliminary studies have shown that the quality of lignites improves with leaching using weak acids for REE recovery²⁹. However, owing to the current prices of REEs, Y, Sc (Fig. S7, Table S10), and the price estimates for the samples studied here, an

economic feasibility of REYSc extraction would require additional uses for coal byproducts. In addition to selling the remaining lignite, some companies use coal and coal byproducts for building materials, such as fire-proof roof tiles that are 2 to 4 times stronger than ceramic tiles⁵⁵. Alternatively, production of activated carbon and/or humic acid from coal has been proposed to make REE extraction economically viable²⁹. Although coal resources in the upper 150 m in the Gulf Coast are plentiful, only five out of 29 coal mines operating since 1983 are currently active, and the San Miguel mine is slated to close by 2027 (Table S13). Coal in the Gulf Coast is mined in open pits and the closed mines are in various stages of remediation (Table S14); only mines in the first phase of reclamation (i.e., covered with ~ 1 m of soil) would be considered accessible for REE production.

In addition to the coal resources, estimated ash deposits at Gulf Coast power plant sites total 375 million tonnes, which include ~ 60% bottom ash and ~40% fly ash (Table S15). Fly ash is considered more suitable for REE extraction because of the smaller grain size⁵⁰. Approximately 70% of the ash is considered potentially accessible (i.e., not sold or used). A total of 20 out of 33 power plants are still active in Texas as of 2024 (Table S15). However, many of the ash ponds have been reclaimed, making it difficult to access ash from these ponds.

Extraction of REEs from coal and coal ash could be used to offset costs of thermal power plant operation and help to improve management of coal ash impoundments and reduce adverse environmental impacts^{56,57}. However, electricity generation from coal has been steadily decreasing since ~2000 and is being replaced by natural gas and renewables, primarily wind and more recently solar power (Fig. S9). The low prices of REEs relative to coal indicate that it is unlikely that REE production would support continued or expanded power generation from coal.

There is also concern about water contamination from leaking ash landfills or ponds because many power plants are located adjacent to water bodies to provide cooling for thermoelectric power generation. Monitoring is required adjacent to coal ash disposal sites and Ashtracker has been compiling data on groundwater contamination related to ash disposal⁵⁸. Many sites have documented groundwater contamination related to coal ash in the Gulf Coast⁵⁸. If those sites need to be remediated, extraction of REEs from coal ash could help offset remediation costs. The USGS Minerals Resources Program evaluates the potential to convert mine waste to resources or “Turn Trash into Treasure”⁵⁹.

4.3 Path Forward

The reconnaissance assessment of REE concentrations in coals in the Gulf Coast provides the initial step to potentially developing REE production in this region. Next steps could include working with

companies operating active mines in the Gulf Coast to determine their interest in developing REEs in their mines. Closed mines can also be evaluated if access is allowed. Although the majority of the mines are closed, there may be opportunities to develop some of the closed mines for REE production, particularly mines such as Gibbons Creek that have high concentrations of REEs. Gibbons Creek has been released from bonded land (Table S14) and could be developed for REEs. Additional sampling would be required to characterize the distribution of REEs and other CMs in more detail. The potential to develop co-products would also be required, including use of activated carbon and/or humic acids.

Samples of combustion ash from active and closed power plants would also need to be analyzed for critical minerals, including REEs. The extractability of REEs could be evaluated, similar to the analysis that was conducted for coal in this study.

Future work could include the scale-up of bench scale, and pilot studies conducted in North Dakota, to evaluate the potential to produce large volumes of mixed REOs from raw coal or combustion ash. Potential discussions with industry groups, could help determine the feasibility of refining the mixed REOs to produce metals of high purity. Impurities could also be evaluated to determine the potential to use those as resources and to minimize waste. Concentrations of CMs and REEs in ponds and landfills that are contaminating nearby water sources could be evaluated for the potential to offset remediation costs with production of REEs. Technoeconomic analysis could evaluate the feasibility of developing economically viable projects according to procedures described for North Dakota lignites.

Conclusions:

The Gulf Coast region has large coal (10s of billions of tonnes) and coal ash (~ 260 million tonnes) resources that could be suitable for extraction of REEs. Analysis of 118 samples from outcrops and coal mine samples in the region shows variable concentrations of total REE + Y (REY) on a dry coal basis (18 to 2,860 ppm) with local hotspots (e.g., Gibbons Creek mine, Texas). The mean REY value for all samples is similar to that in the upper continental crust, with REY to UCC ratios up to 17 in Gibbons Creek mine. Extractability of REEs from the coal is high (median: n 63 to 93%) using environmentally benign weak acid, similar to extractability from lignites in North Dakota. Coal combustion ash from power plants in the Gulf Coast provides another potential source of REEs with ~3 times higher than median REY concentration in coal; however, extractability is generally lower (~20 - 30%)⁴⁹. Average prices of the REEs + Y and Sc results in almost \$8 per tonne of coal and almost \$25 per tonne of ash assuming 50% extractability from pilot tests in North Dakota. These prices underscore how development of co-products, such as activated carbon

and/or humic acid, could enable profitability. REE extraction from ash could be used to offset remediation of water contamination linked to ash ponds or landfills.

This reconnaissance study provides an initial analysis of the potential for developing REEs and other CMs from coal and coal combustion ash in the Gulf Coast. Future studies could expand sampling and analysis and examine the potential for developing additional products to improve economic viability.

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Robert Reedy: Conceptualization, Investigation, Methodology, Formal analysis, Data Curation, Writing – review & editing.

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James Hower: Funding acquisition, Conceptualization, Writing – Review & Editing.

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Nolan Theaker: Funding acquisition, Conceptualization, Methodology, Data curation.

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Data availability:

All data related to this study are provided in Supporting Information.

Declarations

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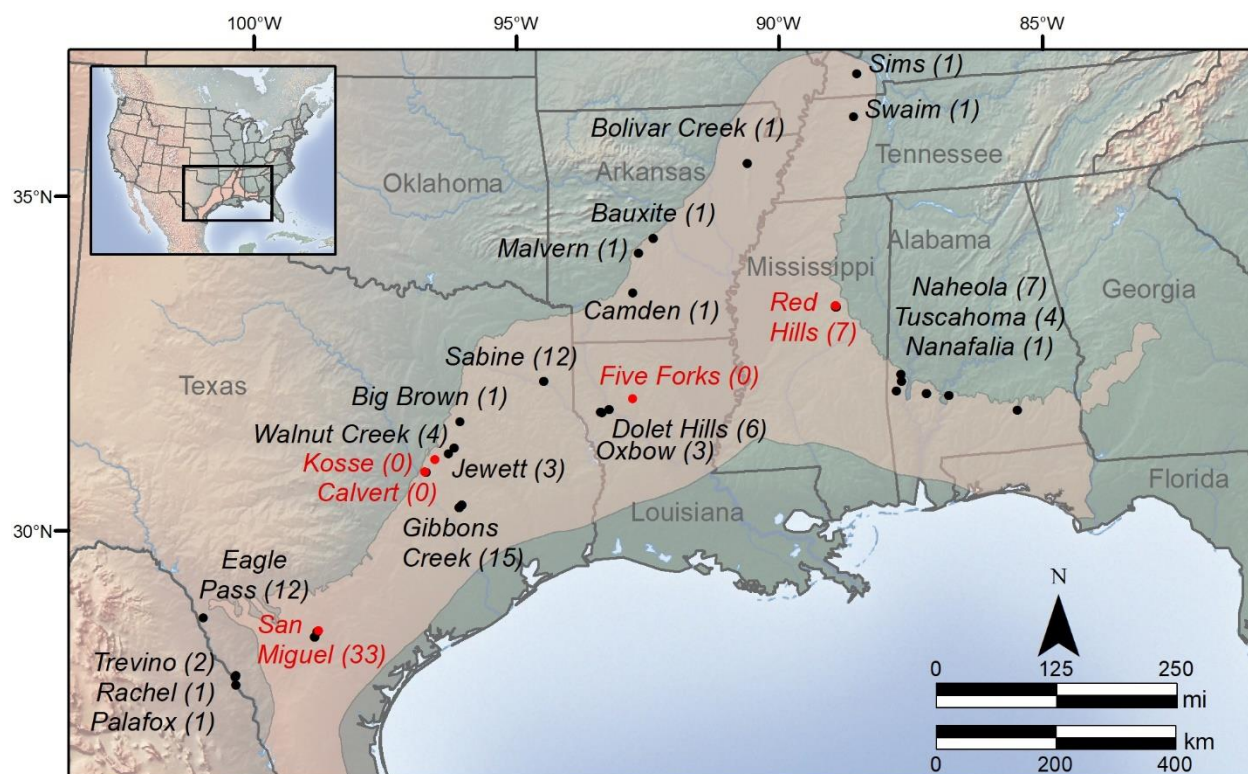


Figure 1. Location of samples analyzed for critical minerals (including rare earth elements, REEs) collected from coal mines and outcrops in the Gulf Coastal Plain region (red font and dots show active mines). Numbers in parentheses indicate the number of samples analyzed at each site. Some of the active mines were not sampled. Trevino, Rachel, and Palafox mines are located near Laredo, Texas. The locations of the sampled sites are provided in Table S2. Base map from Esri³⁷.

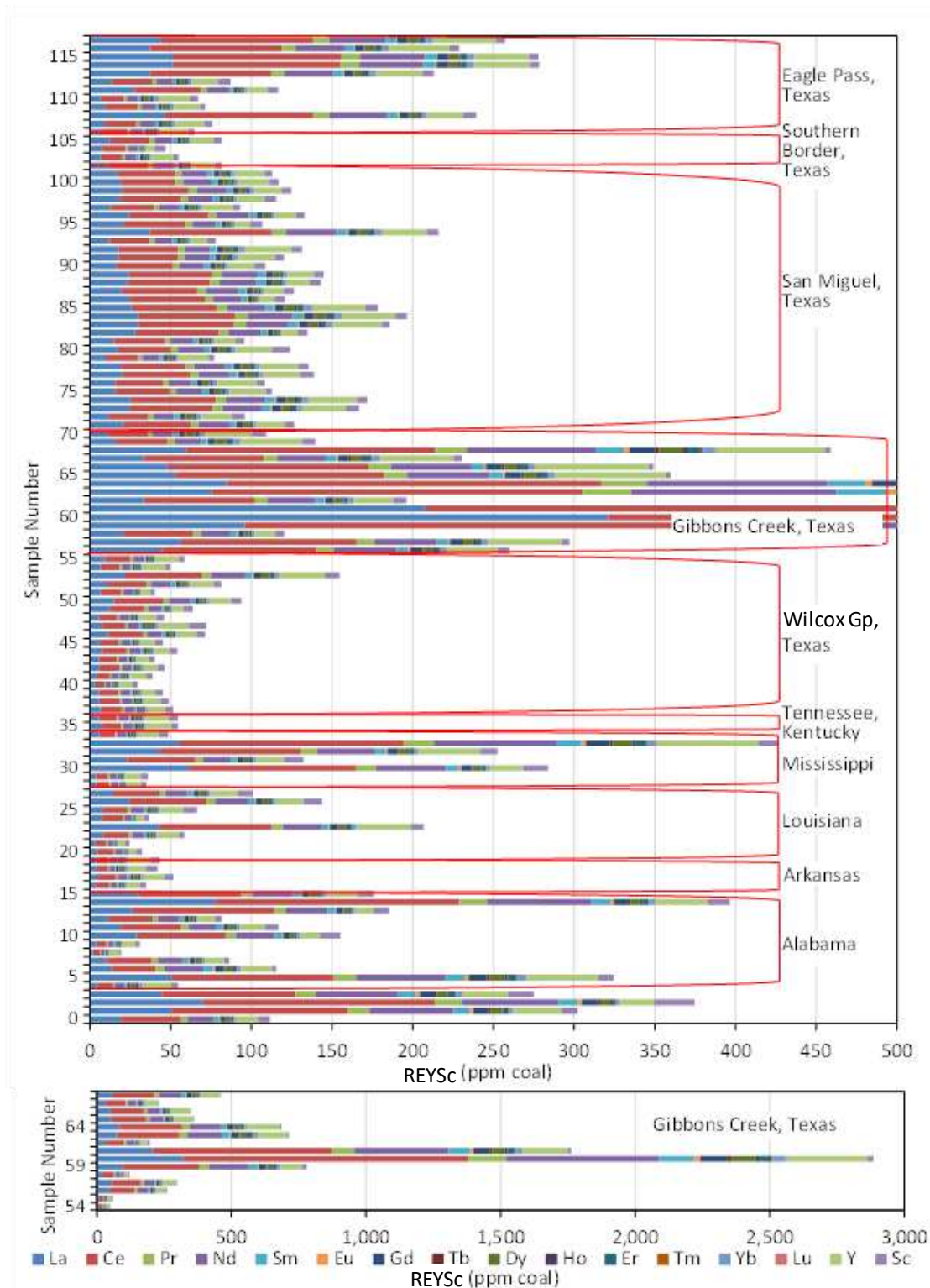


Figure 2. Rare earth element + Y + Sc (REYSc) concentrations in 118 samples from the Gulf Coastal Plain region on a dry coal basis. Samples from Gibbons Creek are shown at a different scale in the bottom. The location of the samples is provided in Fig. 1. The data are provided in Table S3. Gp, Group.

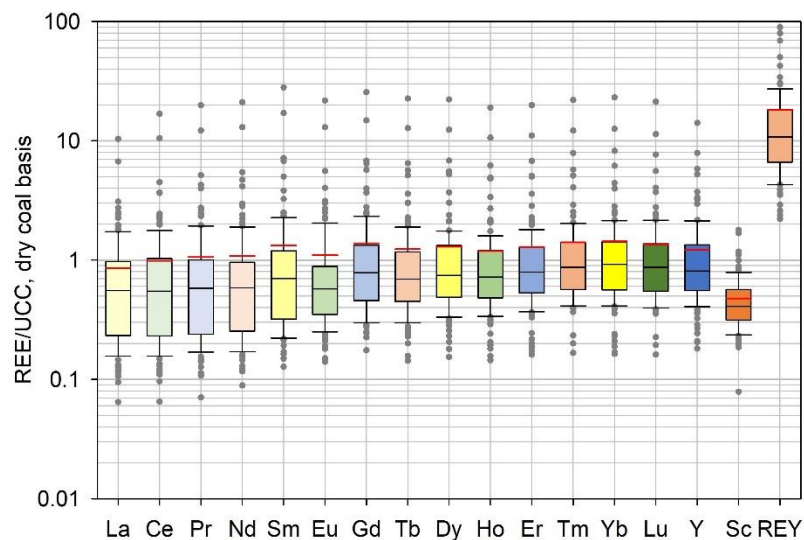


Figure 3. Box plot of the ratio of the distribution of rare earth element (REE) concentrations for 118 samples, including mean and median, 5th and 95th percentiles relative to upper continental crust (UCC) values for each element¹³. Normalization by UCC removes the variability associated with even and odd atomic numbers (Fig. S2). REE data reported on a dry coal basis. Boxes represent 25th to 75th percentiles with black line for median and red line for mean. 5th and 95th percentiles are shown as bars and all sample points are plotted. Data are provided in Table S4.

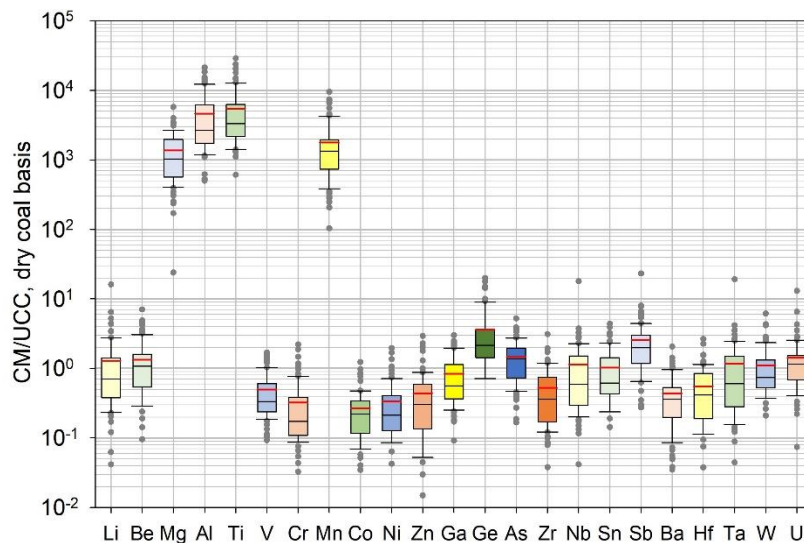


Figure 4. Box plot of the ratio of the distribution of critical mineral (CM) concentrations for 118 samples relative to upper continental crust (UCC) concentrations for each element. These data are reported on a dry coal basis. Boxes represent 25th to 75th percentiles with black line for median and red line for mean. Bars are shown for 5th and 95th percentiles and all sample points are plotted. Data are provided in Table S4.

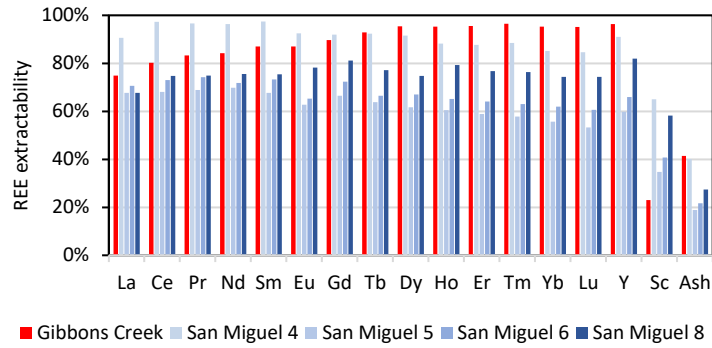


Figure 5. Extractability of rare earth elements (REEs) summing extraction using water, ion exchange, and dilute acid. Extraction of ash from samples also. Data are provided in Table S9.

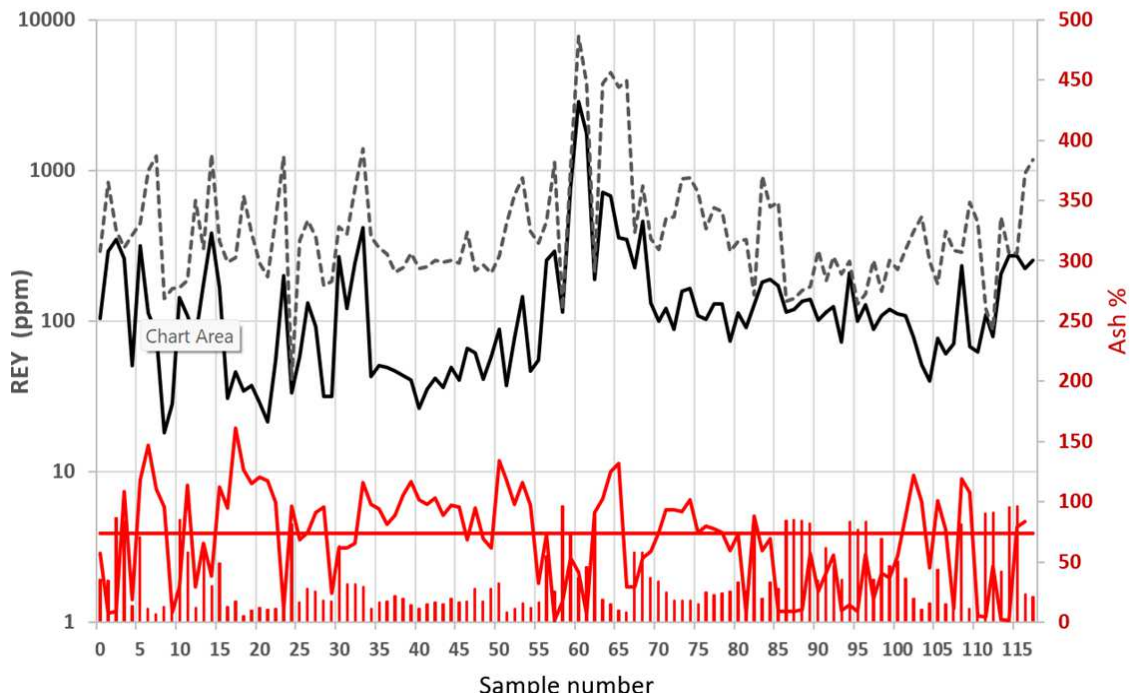


Figure 6. Total REE+Y (REY) in ash (dashed black line), dry coal (solid black line) and ash % (red columns). The ratio of REY in ash versus dry coal (solid red variable line) has a median of 3.9 (horizontal red line). Data are provided in Table S3.

Table 1. Summary data for rare earth elements + Yttrium (REY) and REY + scandium (REYSc) on a dry coal basis and ash basis and value of REY, REYSc in U.S. dollars (USD) per tonne of coal or ash.

Statistic	Concentration (ppm)		Value (USD/tonne)	
	REY	REYSc	REY	REYSc
<i>Dry Coal Basis</i>				
Min.	18	19	0.87	2.38
Max.	2,862	2,885	140.91	173.07
Mean	178	184	7.82	16.95
Median	109	114	4.51	13.50
<i>Ash Basis</i>				
Min.	41	45	1.34	6.54
Max.	7,731	7,794	380.63	467.49
Mean	625	651	27.89	62.78
Median	333	354	14.79	49.20

Table 2. Tradeoffs between using raw coal versus combustion coal ash for production of rare earth elements (REEs). CAPEX, capital expenses. REY concentrations (conc.) are shown on a dry coal basis in the Coal column and an ash basis in the Coal Ash column.

Parameter/ Issue	Coal	Coal Ash
Extraction process	CAPEX mining, reclamation	Low expense licensing, waste to resources
Resources	10s billions tonnes	Landfills and ponds - 260 million tonnes
Status	Active mines, closed mines, reclamation status	Landfill and pond reclamation status
REY conc.	18 to 2,862 ppm Median: 109 ppm	41 to 7,731 ppm Median: 354 ppm
Extractability REY	median: 63 to 93%	~ 20 to 30%
Byproducts	Activated carbon, humic acids	Roof tiles, road material
Environmental Impacts	Active mining, Legacy coal	Legacy ash

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