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CRITICAL MINERALS IN LATE CRETACEOUS COAL BEDS OF THE SAN JUAN BASIN, NEW MEXICO

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Abstract—Critical minerals, including rare earth elements (REE), are becoming increasingly more important in our technological society and are used in many of electronic devices, batteries, and magnets. Rare earth elements include the 15 lanthanide elements (atomic numbers 57 to 71), yttrium (Y, atomic number 39), and scandium (Sc, atomic number 21). They are lithophile elements (elements enriched in the crust) that have similar physical and chemical properties and occur together in nature. In New Mexico, low to moderate concentrations of REE are found in 26 coalfields in Late Cretaceous coal-bearing strata of the San Juan Basin. These rocks are being characterized as part of the U.S. Department of Energy's (DOE) CORE-CM (Carbon Ore, Rare Earth, and Critical Minerals) program. Rare earth elements can be measured in either the entire coal sample before burning (whole-rock basis) or in the ash after burning (ash basis). Because REE become concentrated in ash after burning, REE concentrations in ash are greater than in whole rock. Measuring REE concentrations in ash approximates REE concentrations in the fly or bottom ash remaining after coal is burned at a power plant. Rare earth elements can be leached from power plant ash. Generally, REE concentrations in ash samples are higher on average in lower ash content of coal samples (560 ppm total REE for samples containing <10% ash compared to 234 ppm for samples with >90% ash). Some of the highest total REE concentrations (ash basis) are found in coal ash from the closed La Plata mine in the Fruitland Formation (2,103 ppm total REE), the closed Mentmore mine in the Gallup Sandstone (807 ppm), as well as the Crownpoint (1,684 ppm), Standing Rock (523 ppm), Barker Creek (528 ppm), Mt. Taylor (696 ppm), Star Lake (795 ppm), and Monero (1,026 ppm) coalfields in the San Juan Basin. Additional chemical and mineralogical analyses are necessary to better understand the distribution and origin of critical minerals in coal deposits. As the demand for critical minerals, especially REE, increases because of increased use and restricted supplies, the dollar value per ton of coal, coal mine waste, and ash will rise, enhancing the feasibility of extracting and recovering these economically important minerals.

INTRODUCTION

The growing market demand for alternative technologies like solar panels, wind turbines, batteries, magnets, electric cars, desalination plants, and carbon capture and storage infrastructure require nontraditional elements for their manufacture. In the mining industry, a "mineral" refers to any rock, mineral, or other naturally occurring material of economic value, including metals, industrial minerals, energy minerals, gemstones, aggregates, and synthetic materials sold as commodities. Thus, the term "minerals" as used by the industry includes inorganic substances as well as hydrocarbons, such as oil and natural gas, and carboniferous deposits, such as coal and humate. "Critical minerals" are mineral commodities that are essential to the economic security and national defense of the United States and are from supply chains that are vulnerable to global and national disruption (McLemore and Gysi, 2023).

Coal is a sedimentary rock that is composed of more than 50 wt% organic material and is formed by the compaction of plant material deposited in ancient peat swamps or mires (Hoffman, 2017). Coal is readily combustible and is burned as a fuel in electrical power plants and for home and commercial heating. Coal also is essential in the manufacture of steel, cement, carbon fibers and foams, medicines, tars, and synthetic petroleum-based fuels. Coal also can be a potential source of graphite, a critical mineral that is a major component of batteries. In the future, the concentration of critical minerals, including REE, could be a factor in producing coal deposits.

New Mexico has a wealth of mineral resources, including coal (Hoffman, 2017; McLemore, 2017a). Some critical minerals are associated with various mineral deposits, including coal beds, in the San Juan Basin of New Mexico (John and Taylor, 2016; McLemore, 2017a, 2017b, this volume; McLemore et al., 2024a, 2024b). However, there has been no systematic evaluation of their location or a resource assessment. This project is one of 13 CORE-CM (Carbon Ore, Rare Earth, and Critical Minerals) projects funded by the U.S. Department of Energy (DOE) to identify and quantify the distribution of critical minerals, including REE, in coal beds and related stratigraphic units in basins throughout the United States, including the San Juan and Raton basins. Some coal deposits worldwide are known to contain elevated concentrations of critical minerals, including REE (Dai and Finkelman, 2018; Finkelman et al., 2019; Scott and Kolker, 2019; Dai et al., 2021), but a basin-wide geochemical and mineralogical characterization study of New Mexico coals is needed to determine their potential as a resource for critical minerals. The focus of this CORE-CM project is to identify and quantify the distribution of critical minerals, including REE, in coal beds in the San Juan Basin of New Mexico.

Previous preliminary reports compared the concentration of REE and other critical minerals in coals (whole-rock basis) to adjacent noncoal sedimentary rocks within the San Juan Basin (Badonie et al., 2023; McLemore, 2023; McLemore et al., 2024a, 2024b). This report examines the concentration of REE and other critical minerals on the ash basis after a coal sample is burned. Measuring REE and other critical minerals on the ash basis approximates the critical mineral content of the fly or bottom ash remaining after coal is burned at a power plant, where critical minerals could then be leached from the ash (Geboy et al., 2013; Scott and Kolker, 2019; Dodbida and Fujita, 2023). Furthermore, fly-ash waste stored in ponds and landfills at current and former coal-burning power plants in New Mexico represent an environmental liability. Recovery of critical minerals from these materials during stabilization and closure could help offset closure costs and help with the demand for critical minerals. Future reports will examine the critical minerals potential in coal (whole-rock basis) and adjacent strata and evaluate the economic viability of recovering critical minerals from these rocks.

GEOLOGY

The San Juan Basin is a predominantly Laramide (Late Cretaceous–Early Paleogene) structural basin in northern New Mexico and southern Colorado (Fig. 1) where important energy and mineral resources, including coal, uranium, humate, petroleum, natural gas, and other resources have been or are currently produced (Fig. 2). The stratigraphic units in the San Juan Basin dip inward from the bounding highlands toward the center of the basin, creating a trough-like feature (Brister and Hoffman, 2002; Hoffman, 2017). The Cretaceous sedimentary rocks in the San Juan Basin contain three major coal-bearing units: the Crevasse Canyon, Menefee, and Fruitland Formations. There are 26 defined coalfields in the San Juan Basin (Table 1; Hoffman, 1996, 2017).

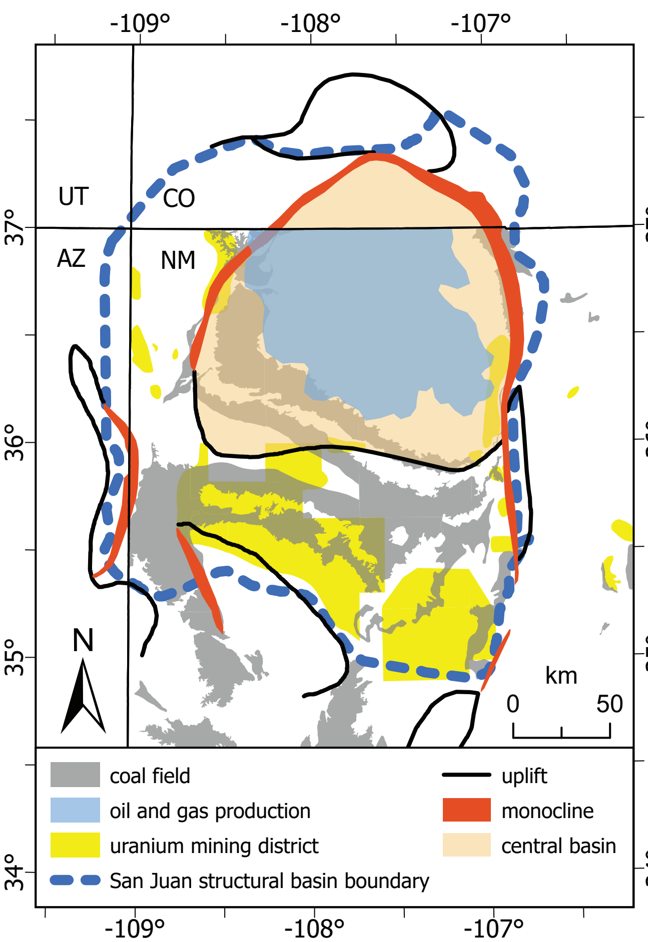

Figure 1. Structural features of the San Juan Basin and adjacent areas. Chaco Slope is the area south of the Central Basin, starting approximately at the subaerial exposure of the Pictured Cliffs Sandstone (from Hoffman, 2017).

Coal in these units has been mined in New Mexico and some production currently fuels electrical generating plants in New Mexico and Arizona. Coal mining on a significant scale began in New Mexico in 1862, when U.S. Army troops from Fort Craig opened the Government mine in the Carthage field (Socorro County) to supply coal for smithing at Forts Seldon, Bayard, and Stanton (Hoffman and Hereford, 2009). Coal mining continued to expand throughout New Mexico in the 1880s to supply the railroads. Three surface coal mines remain in operation today: El Segundo, Lee Ranch, and Navajo (Fig. 1). In 2023, New Mexico was 13th in coal production in the United States, with a recorded production of 7,987,232 short tons worth $226,590,974, all from the San Juan Basin (New Mexico Energy, Minerals and Natural Resource Department, 2024). However, production is decreasing because of mine closures due to closures of coal-fired electrical generating plants. Furthermore, the coal at some mines is deeper in the subsurface and more expensive to mine. New Mexico was 10th in estimated recoverable coal reserves in the U.S. in 2023 (28 million short tons of recoverable reserves at mines and 6,694 million short tons estimated recoverable reserves in the basin).

Several factors of a coal resource determine whether a deposit is economic: (1) geologic factors (quality, overburden thickness, coal thickness), (2) the technology available for extraction, (3) distance to a market, (4) available transportation network, (5) environmental issues, and (6) permitting. The closure of coal-fired power plants has resulted in decreased coal production, including the cancellation of planned mines. Throughout the history of coal mining in New Mexico, these factors have changed and continue to evolve.

Coal contains noncombustible minerals that become part of the ash after burning. This ash, along with other mine wastes, may contain REE and other critical minerals at concentrations that could be recoverable in the future (Scott and Kolker, 2019; U.S. Department of Energy, 2022; Liu et al., 2025). Elevated concentrations of critical minerals, including REE, in these materials could become a future factor in the evaluation of the economics and feasibility of mining coal deposits in New Mexico and/or recovering these critical minerals from the mine wastes and fly ash deposits.

METHODS

Sample Collection

Different strategies were employed based upon the purpose of each sampling task (McLemore and Owen, 2024). Several types of samples were collected including composite, select, profile, and drill core samples as described below. Samples were archived at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) for future examination. Two separate splits of each sample were generally collected and stored in sealed plastic bags, or, for larger samples, plastic buckets with lids: one split for chemical analyses and a second split to be archived. Location information by global positioning system (GPS), type of sample, and field and laboratory petrographic descriptions were recorded for each sample. Geologic observations were recorded on a field description form or in field books. Hand specimen descriptions included what was collected, petrographic descriptions, and information on samples for the laboratories (samples elevated in sulfur may be treated differently than ones containing less sulfur). The hand specimen descriptions provided the preliminary data required to determine what samples would need specific detailed analyses. The location, type of sample, and other descriptive data were entered into the project database housed on a server at the NMBGMR.

Composite and select samples were collected for this study between 2021 and 2024. Composite samples were collected along the width and thickness of a sedimentary layer or along the surface of a mine waste pile in order to obtain representative samples. Select samples included hand specimens of mineralized rocks (including coal samples) and grab samples from a mine waste pile. Weathered surfaces were removed from rock samples. Samples for geochemical analysis were broken into smaller pieces. Select samples were generally collected directly from an outcrop or the base of mine waste pile slopes to avoid sampling of solely float material.

Profile samples were generally collected along a vertically exposed section. A pick or trowel was used to gently clean the surface to prevent the boundary lines from caving in when sampling. Changes in lithologies (i.e., composition, color, thickness, texture, and grain size) were recorded with their respective depths. One GPS location and waypoint were assigned to the profile and each sample was assigned a separate sample ID for each lithology.

Drill core samples were collected from existing drill core stored at the NMBGMR Core Facility in Socorro. Drill cores were generally described (logged) and photographed before sampling. Only half of the core was split or sawed, with the remaining core left in the box undisturbed. If the core had already been sampled, then only a quarter of the original drill core was sampled and removed for testing.

General precautions to limit sources of contamination were followed, including cleaning all equipment between samples and ensuring tools (buckets, sampling bags, shovels, trowels, and sieves) were constructed of materials suitable for environmental sampling (typically stainless steel, plastic, or aluminum). Devices plated with chrome or other materials were not used because they could introduce contaminants to the samples. Disposable latex or nitrile gloves were worn while sieving to avoid contamination.

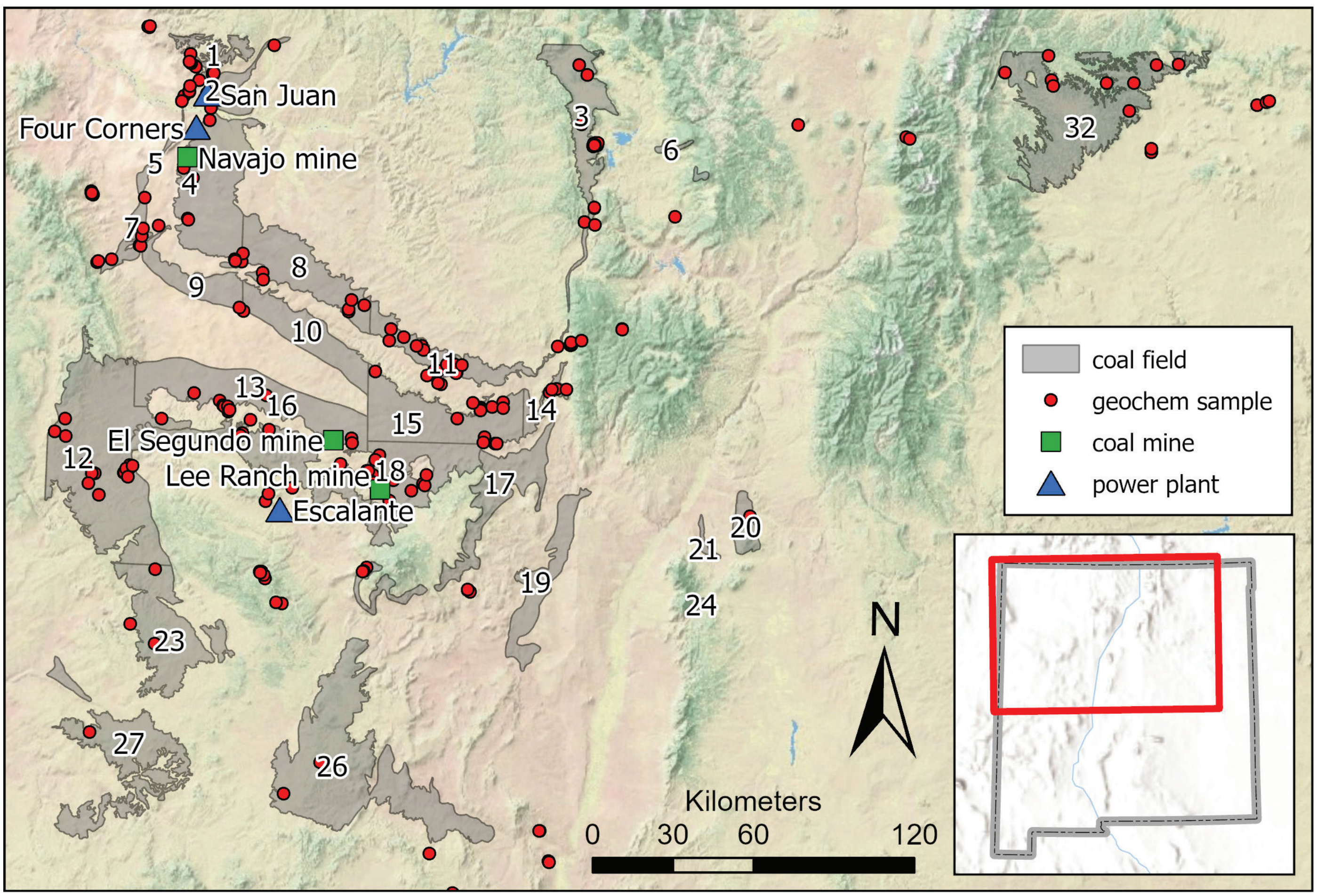

Figure 2. Location map of coalfields, mines, power plants, and geochemical samples in the San Juan and Raton basins, New Mexico. Coalfields are named and summarized in Table 1. Active coal mines are surface operations. The Lee Ranch mine suspended operations in 2016, but reopened in 2024. Only the Four Corners power plant remains active in New Mexico.

Samples were prepared for analysis at NMBGMR. Selected samples were cut into billets that were sent to a laboratory for preparation of polished thin sections. Aforementioned splits of samples were sent to a laboratory for chemical analyses. Internal standards that NMBGMR maintains were submitted as "blind samples" to the commercial laboratory with each batch to evaluate and control analytical quality.

Geochemical Analyses

Geochemical data are critical for the evaluation of critical mineral resources. Geochemical analyses of samples were conducted by ALS Global, SGS, and the University of Kentucky. Coal samples were crushed to −20-mesh (850 µm screen openings). Duplicate samples and standards were analyzed, and analytical uncertainty was generally <5%. Selected samples were submitted to a different laboratory to check analytical accuracy between laboratories for quality assurance and control and results are comparable. Rare earth elements at University of Kentucky were measured using ICP-OES. Rare earth elements at ALS and SGS were measured by ICP-MS. Geochemical plots were created using ioGAS-64™ software. Chemical analyses are in Appendix 1.

TABLE 1. Summary of coal samples from coalfields in the San Juan Basin.

District ID	District/Coalfield	Year of Initial Production	Year of Last Production	Formation	Number of Samples Analyzed	Number of Coal Samples Analyzed	Demonstrated Resources, 10^6 tons (Hoffman, 2017)
DIS257	Barker Creek (1)	Unknown	1905	Menefee	9	6	183
DIS150	Bisti (8)	1980	1988	Fruitland	54	19	872
DIS208	Carthage (29)	1861	1963	Crevasse Canyon, Tres Hermanos	2	2	30
DIS181	Cerrillos (20)	1882	1962	Menefee	2	2	46.5
DIS259	Chaco Canyon	1905	Unknown	Menefee	3	2	46
DIS260	Chacra Mesa (15)	Unknown	1945	Menefee	43	15	140
DIS118	Crownpoint (16)	1914	1951	Crevasse Canyon	12	8	663
N/A	Dakota	-	-	Dakota	5	5	Unknown
DIS262	Datil (26)	1917	1940	Dakota	2	2	47
DIS155	Fruitland (2)	1889	2001	Crevasse Canyon, Tres Hermanos	11	10	550
DIS119	Gallup (12)	1882	2001	Fruitland	50	27	610
DIS156	Hogback	1907	1971	Crevasse Canyon	10	0	66
DIS264	Jornada del Muerto (28)	Unknown	1927	Menefee	6	3	0
DIS174	La Ventana (14)	1904	1983	Crevasse Canyon	5	5	263
DIS146	Monero (3)	1882	1970	Menefee	62	13	40
DIS016	Mount Taylor (17)	1952	1953	Menefee	8	6	19
DIS157	Navajo (4)	1963	Present	Crevasse Canyon	19	9	1340
DIS258	Newcomb	-	-	Fruitland	3	0	126
DIS021	Raton (32)	1898	2002	Menefee	65	26	Unknown
DIS003	Rio Puerco	1937	1944	Vermejo, Raton	0	0	25
DIS009	Salt Lake (27)	1987	1987	Crevasse Canyon	2	1	323
DIS121	San Mateo (18)	1983	Present	Moreno Hill	9	4	385
DIS097	Sierra Blanca (30)	1899	1958	Crevasse Canyon	8	4	42
DIS261	Standing Rock (13)	1952	1958	Menefee	24	4	392
DIS158	Star Lake (11)	-	-	Menefee	51	29	946
DIS263	Tierra Amarilla	1955	1955	Fruitland	0	0	4.5
DIS159	Toadlena (7)	-	-	Menefee	16	6	0
DIS124	Zuni (23)	1908	1926	Menefee	1	1	83
	Other samples				140	0	
	Totals				622	209	7,153.5

Notes: Coal fields and reserves are delineated by Hoffman (1996, 2017). District ID is from the New Mexico Mines Database (McLemore, 2017a). The number in parentheses following the district/coalfield corresponds to the numbering used in Figures 2 and 3.

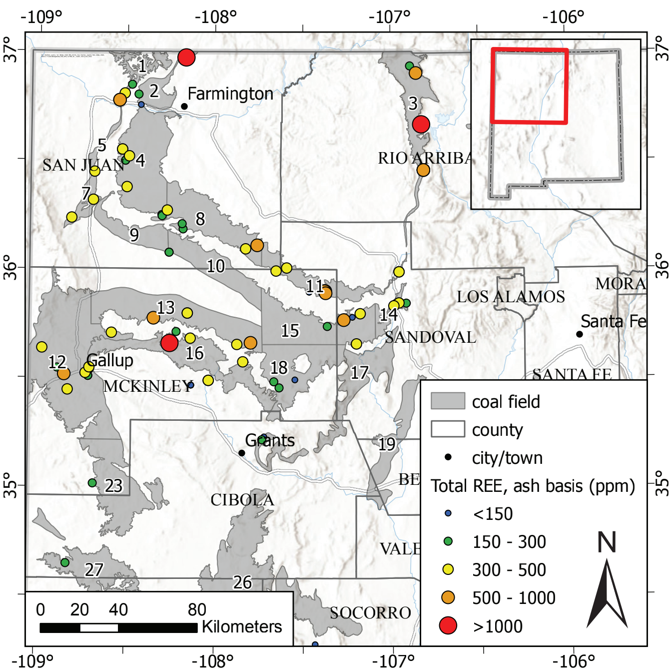

Figure 3. REE in coal ash in the San Juan Basin. See Table 1 for the names of coalfields. Chemical analyses are in Appendix 1.

Petrography and Mineralogy

Thin sections were scanned in both plane and cross-polarized light, selected photomicrographs were taken, and petrographic descriptions were entered into the database. Mineralogy of selected samples was determined by visual, optical, and X-ray diffraction (XRD) methods. Whole rock or mineral separate XRD analyses were performed using a PANalytical X-Pert PRO® diffractometer at NMBGMR or at the University of Kentucky. Analyses were conducted using 45 kV X-ray beam tension and 40 mA X-ray beam current and XRD patterns were examined using X'Pert HighScore Plus® software that identifies intensity peaks and matches patterns to a Powder Diffraction File database containing known mineral phases. These data will be available in a future report.

RESULTS AND DISCUSSION

Although electron microprobe studies are planned to identify minerals hosting specific critical minerals, it is likely that they include clay minerals (which can adsorb REE), zircon ($ZrSiO_4$), ilmenite ($FeTiO_3$), monazite ($[Ce,La]PO_4$), and rutile/anatase (TiO_2), as determined from petrographic and XRD analyses. Quartz and feldspars are also common in the studied samples. Figures 4 through 9 show some geochemical plots of critical minerals in coal samples from the San Juan Basin. Concentrations of REE on ash basis are higher on average in lower (<10%) ash content samples (Fig. 4) with an average of 560 ppm total REE compared to 234 ppm for samples with >90% ash. Coal ash samples in this study typically displayed relatively flat to slightly light REE enriched chondrite-normalized REE patterns (Fig. 5), consistent with REE hosted by clay minerals, zircon, and monazite. When normalized to shale (North American Shale Composite; Haskin and Haskin, 1966), these coal ash samples display flat REE patterns with no significant enrichment or depletion (Fig. 6). Box and whisker plots (Figs. 7–9) show the concentrations of REE, scandium, and lithium, respectively. A box and whisker plot provides a visual representation of a data distribution, illustrating the minimum and maximum range as whiskers along with the median value and quartile ranges as boxes of a given dataset. On an ash basis,

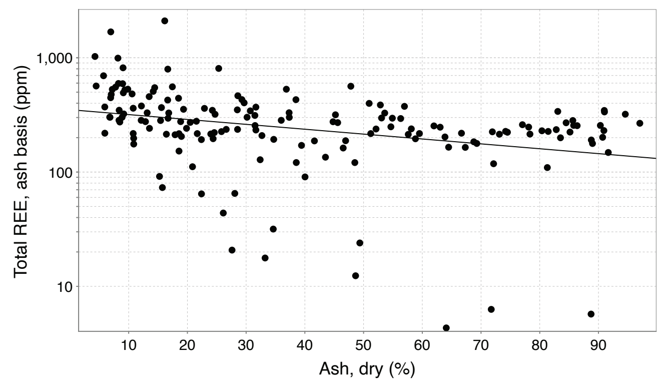

Figure 4. Total REE versus ash content of coal samples from the San Juan Basin. The fine black line is a line of best fit. Note higher total REE are found in samples with lower ash contents. Chemical analyses are in Appendix 1.

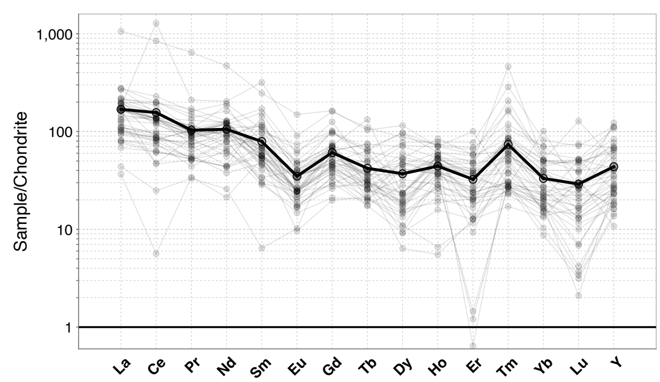

Figure 5. Chondrite-normalized (sample/chondrite) REE diagram of New Mexico coal samples (ash-basis) showing the relatively low concentrations of REE compared to REE deposits currently in production. Chondrite values from Taylor and McLennan (1985). Chemical analyses are in Appendix 1.

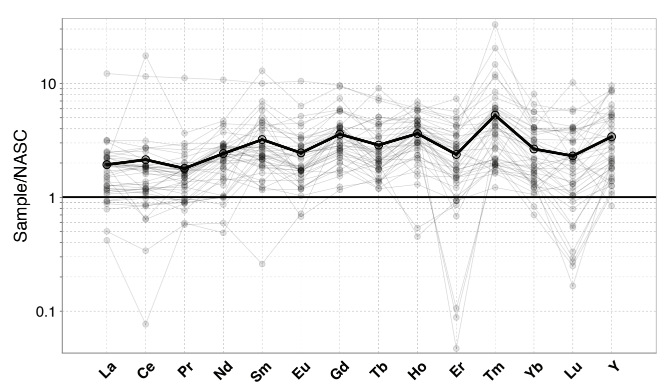

Figure 6. Diagram of New Mexico coal samples (ash-basis) normalized to North American Shale Composite (NASC; Haskin and Haskin, 1966). The bold line represents the average. Chemical analyses are in Appendix 1.

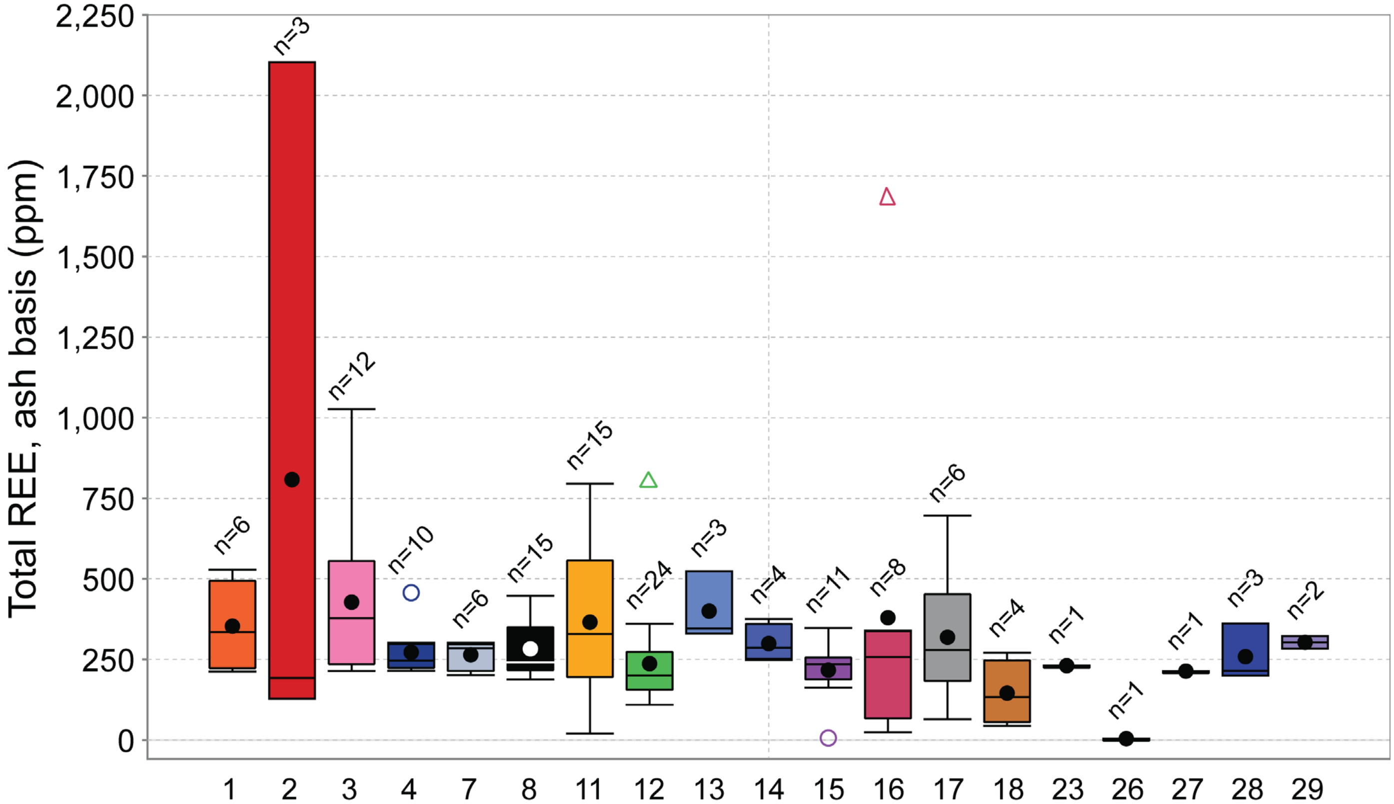

Figure 7. Box and whisker plot of total REE on an ash basis (in ppm) by coalfield. Numbers along the x axis correspond to the coalfields in Table 1. n = number of samples. Chemical analyses are in Appendix 1.

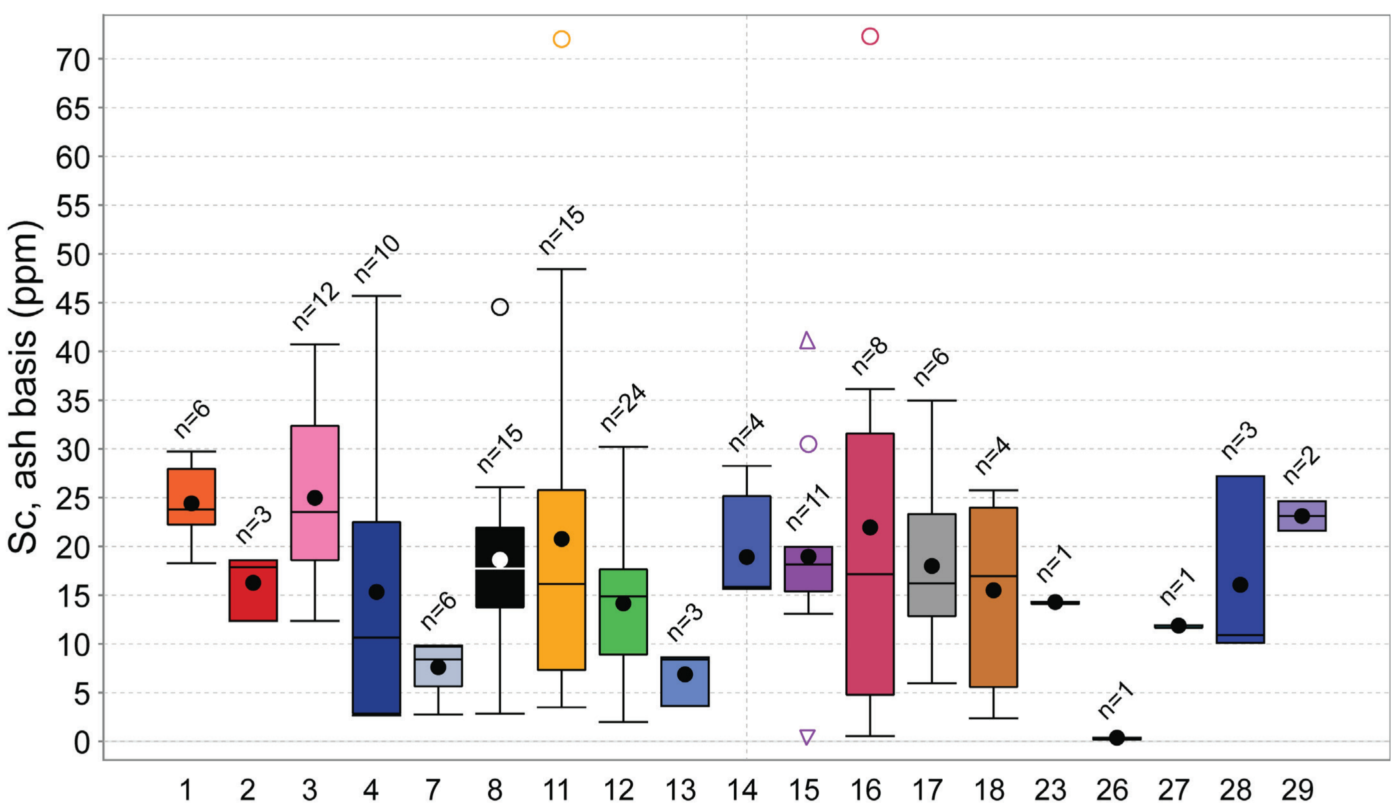

Figure 8. Box and whisker plot of scandium on an ash basis by coalfield. Numbers along the x axis correspond to the coalfields in Table 1. n = number of samples. Chemical analyses are in Appendix 1.

these coal samples generally contain less than 500 ppm total REE, though a sample from the La Plata mine contains as much as 2,103 ppm. Scandium concentrations are generally less than 30 ppm, with some samples reaching as high as ~80 ppm. Concentrations of lithium average around 20 ppm, though several samples contain as much as ~90 ppm (Appendix 1). The Department of Energy considers samples containing >500 ppm REE potentially economic in the future (U.S. Department of Energy, 2022).

CONCLUSIONS

Some of the highest total REE concentrations (ash basis) are found in coal ash from the closed La Plata mine in the Fruitland Formation (2,103 ppm), the closed Mentmore mine in the Gallup Sandstone (807 ppm), as well as the Crownpoint (1,684 ppm), Standing Rock (523 ppm), Barker Creek (528 ppm), Mt. Taylor (696 ppm), Star Lake (795 ppm), and Monero (1,026 ppm) coalfields in the San Juan Basin (Appendix 1). Common minerals hosting the critical minerals in these rocks include clay minerals, zircon, ilmenite, monazite, and rutile/anatase. Clay minerals can adsorb REE. Monazite is a primary REE mineral and is an important ore mineral in some REE mineral deposits. Zircon is an important source for zirconium, and ilmenite, rutile, and anatase are sources for titanium.

More chemical and mineralogical analyses are required to fully understand the distribution and origin of REE and other critical minerals in these deposits. Electron microprobe studies are planned in the future to identify specific minerals that host the critical minerals, especially REE. As the demand for some of these elements increases and shortfalls in supply occur, their value is expected to increase. This could eventually enhance the potential economic benefits of some coal and other mineral deposits. Ultimately, feasibility of mining these resources may depend upon production of more than one commodity, new and more cost-effective extraction technologies, as well as other considerations.

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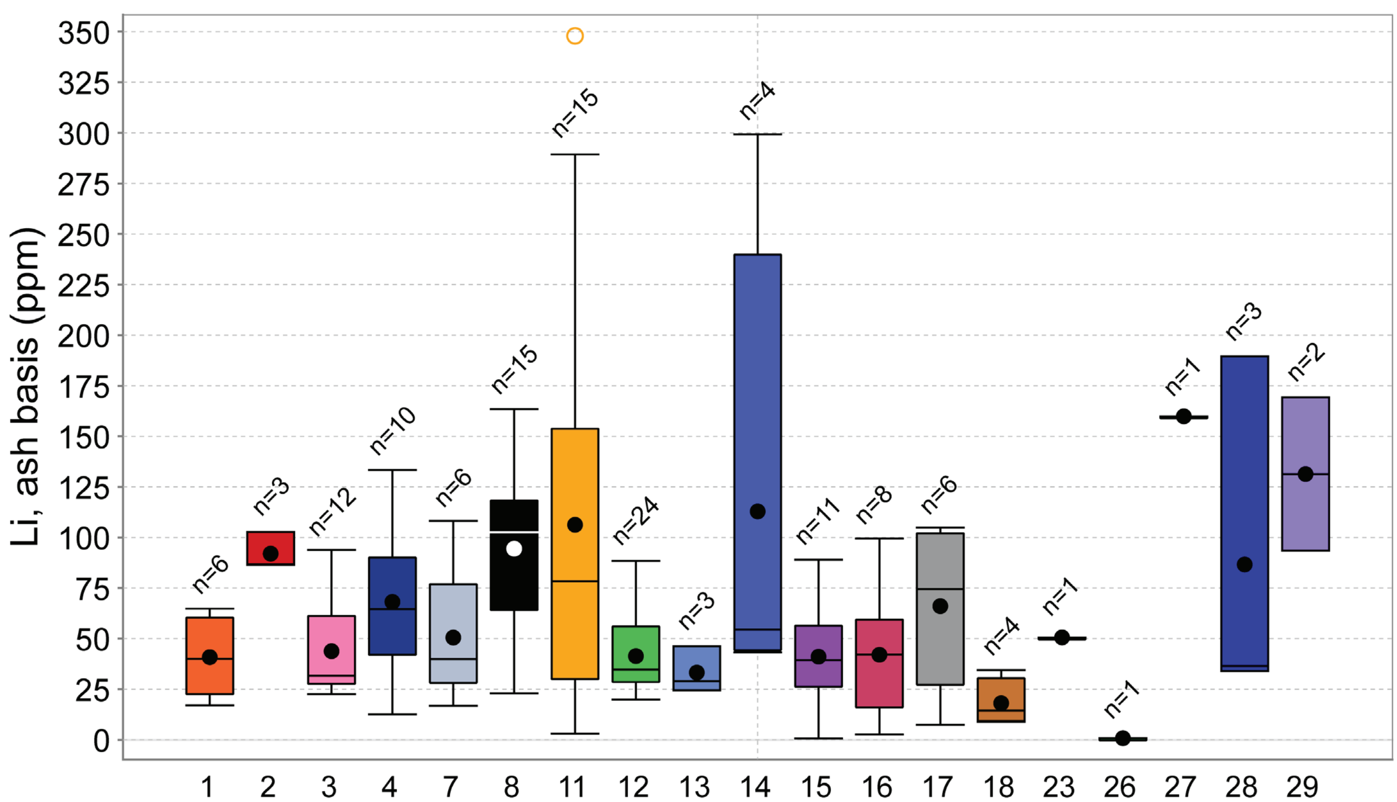

Figure 9. Box and whisker plot of lithium on an ash basis (in ppm) by coalfield. Numbers along the x axis correspond to the coalfields in Table 1. N = number of samples. Chemical analyses are in Appendix 1.

its endorsement, recommendation, or favoring by the United States government, NMBGMR, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for and receive a permit from the Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515, and telephone no. 928-871-6588.

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Appendix can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2025006