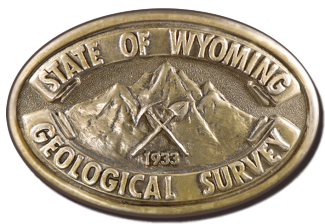*Interpreting the past, providing for the future*

# Trace Element Geochemistry of Coal Deposits in the Adaville and Frontier Formations, Kemmerer Coal Field, Wyoming

Kelsey S. Kehoe, Garrett W. Gay, and Janet C. Dewey

**Wyoming State Geological Survey**

Erin A. Campbell, Director and State Geologist

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Layout by James R. Rodgers

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## ABSTRACT

This report shares the results of trace element analyses from select coals and associated deposits in the Adaville and Frontier formations in the Kemmerer coal field of western Wyoming. More than 60 samples of coals, shales, partings, and other associated lithologies were collected and analyzed. To improve understanding of trace element distribution within coal deposits, sampling targeted exposures where a series of samples could be collected from discrete positions within a coal and its bounding beds. Samples were analyzed for trace elements that are commonly considered "critical" due to their integral role in many advanced and high-demand technologies. Results from this study indicate that the majority of samples contain concentrations of these elements at amounts comparable to global averages. Variations in concentrations appear to be closely linked with lithology changes and ash yield, agreeing with trends noted in other coal deposits.

## INTRODUCTION

Historically, coal has been used to generate heat, power, and coke. Previously published analyses of trace elements in coals were therefore typically acquired with these end uses in mind, focused on the effects of composition on coal utilization and environmental impacts (Swaine, 1990). Less common was research focused on the potential of coals to host economically valuable elements, though publications dating back to the early 1900s have noted anomalously enriched coal and coal byproducts (Stone, 1912; Goldschmidt, 1935). Throughout the 20th century, technological advances spurred intermittent exploration primarily focused on uranium (U) and germanium (Ge) from coal (Masursky, 1962; Swaine, 1990; Finkelman and Brown, 1991).

Since the 1990s the magnitude and scope of prospecting for coal-related ore deposits, including coal byproducts, has increased dramatically around the world, driven by reports of elevated levels of rare earth elements (REEs; here defined as the 14 naturally occurring lanthanide elements plus yttrium [Y] and scandium [Sc]), gallium (Ga), Ge, and other elements that are in high demand for their uses in advanced materials and technologies (Seredin, 1996; Hower and others, 1999; Seredin and Finkelman, 2008; Dai and others, 2012; Mastalerz and Drobniak, 2012; Hower and others, 2016; Wagner and Matiane, 2018). Subsequent research has expanded to investigate byproducts that concentrate REEs (Kolker and others, 2017; Dai and Finkelman, 2018; Lefticariu and others, 2020), as well as associated strata, like bounding roof and floor rock, which can have higher concentrations of valuable trace elements than their adjacent coals (Rozelle and others, 2016; Mastalerz and others, 2020).

Efforts to develop commercially feasible extraction methods for REEs and other elements from both coals and coal byproducts are ongoing (Dev and others, 2020; Honaker and others, 2020; Montross and others, 2020; Zhang and Honaker, 2020). Ge is currently commercially produced from coal deposits in China and Russia (Shanks and others, 2017; Dai and Finkelman, 2018).

Many of these elements were identified as critical by the U.S. Government (U.S. Department of the Interior, 2018; Fortier and others, 2018; Nassar and Fortier, 2021). Critical minerals are elements with unique applications in technology and national security, which have global supply chains that are potentially at risk of interruption. These elements are integral components of electronics, battery technology, solar panels, and wind turbines. This official designation, coupled with expanded funding from both the U.S. Department of Energy and U.S. Geological Survey (USGS), has intensified the amount of research devoted to characterizing the critical mineral content of domestic coals and associated rocks, as well as possible methods of development (Bryan and others, 2015; Lin and others, 2018a, 2018b; Tetra Tech, 2018; Bagdonas and others, 2019; Hammarstrom and others, 2020; Yang and others, 2020).

Currently, the primary source of trace element chemistry for U.S. coal deposits is the COALQUAL database (Finkelman and others, 1994; Palmer and others, 2015), which is a compilation of coal quality and chemical data

that is a subset of the USGS's National Coal Resources Data System. Several national and regional evaluations of critical mineral content in coals have relied on the COALQUAL data (Bryan and others, 2015; Lin and others, 2018a, 2018b; Tetra Tech, 2018).

Additional data for Wyoming coal deposits would provide a more thorough understanding of trace element distribution and the potential for critical mineral enrichment. An assessment of the COALQUAL database by Lin and others (2018a) indicates that Wyoming coals are underrepresented in the database relative to their proportion of the national demonstrated reserve base. A subset of the COALQUAL samples from the Kemmerer coal field have trace element data, but these samples were collected from the mined portions of the coal beds to represent the "as used" coal product (Glass, 1975), resulting in an incomplete dataset for these deposits.

This report aims to improve understanding of trace element occurrences in coal deposits within the Frontier and Adaville formations in the Kemmerer coal field in western Wyoming (fig. 1). By targeting samples from discrete locations within coal beds and their bounding strata, this study contributes additional data to aid in clarifying how trace elements are distributed within coal deposits of the Kemmerer coal field, and how their occurrences affect the critical mineral potential of these deposits.
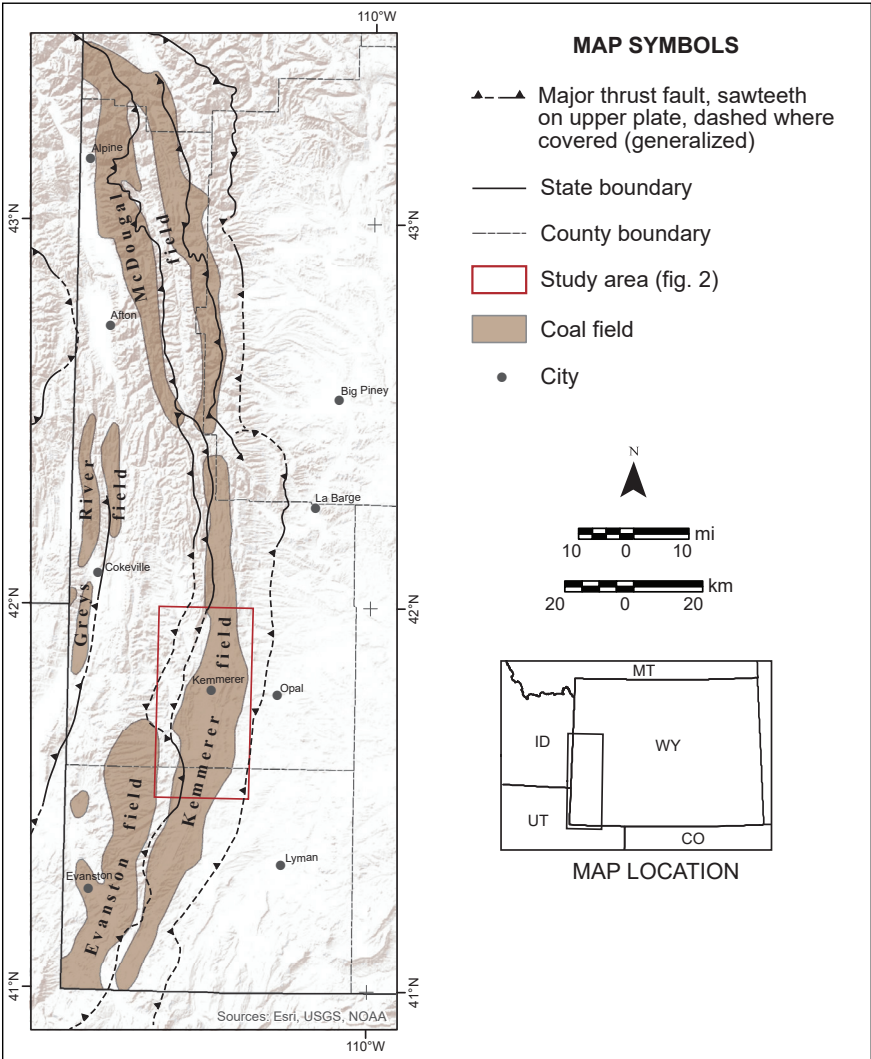


**Figure 1.** Map of western Wyoming, showing coal fields within the Hams Fork coal region, the extent of this study area, and the major faults associated with the Overthrust belt. Thrust faults are generalized and modified from Royse (1993).

**Geologic Setting**

The Kemmerer coal field extends from Lincoln County into northern Uinta County, and is part of the Hams Fork coal region in western Wyoming (fig. 1). It includes coals within the Upper Cretaceous Adaville and Frontier formations exposed within the Lazeart syncline (fig. 2), which is a long, narrow, north-trending fold that parallels thrust faults associated with Sevier deformation in the Overthrust belt. As a result of this deformation, coal beds in the area typically dip 20–30 degrees westward, and offset along faults ranges from several hundred to more than 4,500 m (about 15,000 ft; Rubey and others, 1975).

Both the Adaville and Frontier formations were deposited along the western edge of the Cretaceous foreland basin, where coastal plain, littoral, and shallow marine environments of the Western Interior Seaway migrated across the region (Roberts and Kirschbaum, 1995). The Cenomanian to Coniacian Frontier Formation consists of nearshore and coastal deposits, and the Santonian to Campanian Adaville Formation was deposited in beach and coastal plain settings (Roehler and others, 1977; Roberts and Kirschbaum, 1995; Lynds and Slattery, 2017). Between the two units is the Hilliard shale, which overlies the Frontier Formation and underlies the Adaville Formation. Marine rocks of the Hilliard Shale represent a large-scale transgression of the sea westwards.

Coals in the Frontier Formation are divided into three stratigraphic coal groups: the Spring Valley coal group near the base (also known as the Carter coal group), the Willow Creek coal group in the middle of the formation, and the Kemmerer coal group (not to be confused with the Kemmerer coal field, a spatial designation that encompasses all mineable coal deposits in the Kemmerer area), which is in the upper part of the formation above the Oyster Ridge Sandstone Member. Spring Valley group coals are high volatile C bituminous (Townsend, 1960), and Willow Creek group coals are high volatile B to A bituminous (Berryhill and others, 1950). Coals in the Kemmerer group are high volatile B bituminous to high volatile C bituminous (Townsend, 1960). Most of these coals are less than 2 m (6 ft) thick (Glass, 1982).

In the Adaville Formation, coals are more common in the lower half of the unit, above the basal Lazeart Sandstone Member. Adaville Formation coals are thicker and more abundant than those in the Frontier Formation, but are lower rank, ranging from subbituminous B to C (Glass, 1982). The thickest Adaville coal bed, which is immediately above the basal Lazeart Sandstone Member, averages 24 m (80 ft) in the Kemmerer area (Glass, 1982).

Both formations have been the targets of mining for decades. Starting in the 1860s, early operations produced coal primarily from the Frontier Formation using underground methods. Surface operations became more common in the 1960s as demand from coal-fired generating stations increased (Engstrom, 1977). Currently, one mine operates in the region—the Kemmerer Mine, which produced 3 and 2.5 million short tons from the Adaville Formation in 2019 and 2020, respectively (Mine Safety and Health Administration, 2021).

## METHODS

**Sample Collection**

Sixty-three samples of coals and associated strata were collected from the Frontier and Adaville formations in order to better understand the occurrence and distribution of trace elements throughout the Kemmerer coal field. Field work was completed during summer 2020. More than 20 locations were sampled in the area (fig. 2), ranging from fresh outcrops in the Kemmerer Mine (fig. 3) to surface exposures, which required excavating pits and trenches to obtain unweathered material. Depending on the site location and bed thickness, multiple samples were collected along a transect perpendicular to the coal and bounding non-coal beds, targeting specific stratigraphic positions (fig. 3) as opposed to continuous channel or bench sampling. Sampled lithologies are coal, underclay, carbonaceous shale, clay-rich roof rock, partings, sandstone, and clinker. Sample details and locations are included in Appendix 1, Table A1–1. All samples were collected and stored in double-bagged 3.8-liter (1 gallon) polyethylene bags.

**MAP SYMBOLS**

| | |
|---|---|
| ——— | Geologic contact |
| ▲····▲· | Thrust fault, sawteeth on upper plate, dotted where covered (generalized) |
| •——•— | Normal fault, bar and ball on downdropped block |
| ✸···✸ | Lazeart syncline, dotted where covered |
| –··–··– | Extent of Kemmerer Mine |
| • K25 | Sampling location |
| ● | City |

**MAP UNITS**

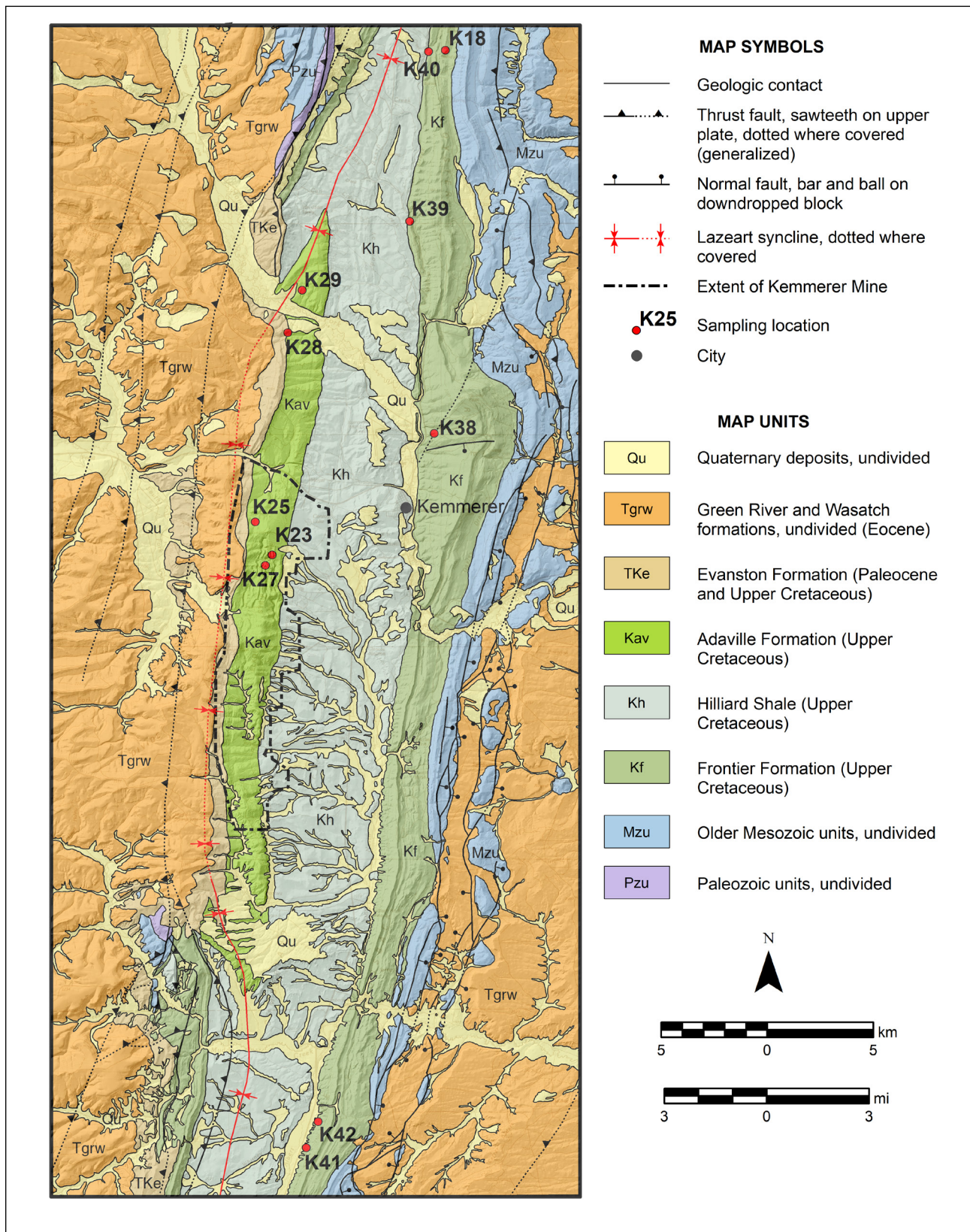| | |
|---|---|
| Qu | Quaternary deposits, undivided |
| Tgrw | Green River and Wasatch formations, undivided (Eocene) |
| TKe | Evanston Formation (Paleocene and Upper Cretaceous) |
| Kav | Adaville Formation (Upper Cretaceous) |
| Kh | Hilliard Shale (Upper Cretaceous) |
| Kf | Frontier Formation (Upper Cretaceous) |
| Mzu | Older Mesozoic units, undivided |
| Pzu | Paleozoic units, undivided |

**Figure 2.** Generalized geologic map of study area with sample locations. Extent of this map shown in fig. 1. Modified from the geologic maps of M'Gonigle and Dover (2004) and Love and Christiansen (1985).
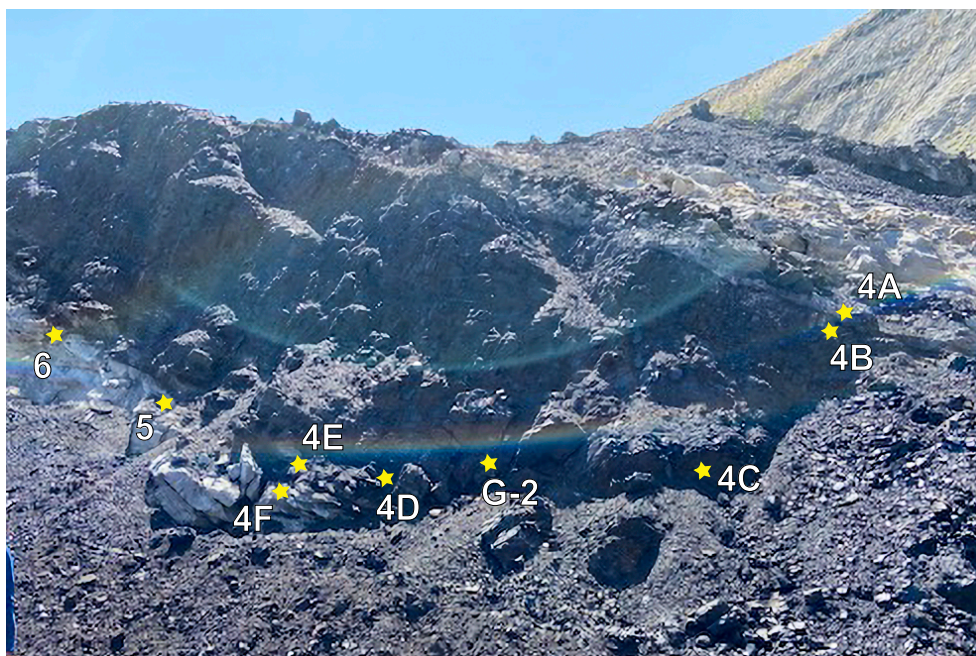
**Figure 3.** Annotated photograph of Adaville Formation coal bed 1055 exposed in the 10a pit at the Kemmerer Mine. Samples were collected both vertically and laterally across bedding, and are labelled with the last segment of each sample name (all samples begin with "KK-082620-"). The coal bed is approximately 3.7 m (12 ft) thick, overlain by a silty shale and underlain by a clay-rich carbonaceous shale.

An additional seven coal samples were obtained from the Kemmerer Mine's Sorenson Tipple. Each sample represents the portion of a coal bed mined over the course of one hour. They were collected from the sort sample system and pulverized to 8 mesh. During mining, the upper- and lowermost 0.15 m (0.5 ft) of the coal bed are excluded from production in order to meet specific coal quality requirements.

**Preparation and Analysis**

Samples were prepared and analyzed for trace element geochemistry in the Aqueous Geochemistry Laboratory at the University of Wyoming Department of Geology and Geophysics.

Sample preparation entailed drying, pulverizing, ashing, fusion, dissolution, and dilution prior to analysis by inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS).

Aliquots of each sample were pulled randomly from sample bags for preparation. These were dried in an oven at 107°C (225°F) for eight hours to remove adsorbed moisture. Dried samples were pulverized in a ball mill until uniformly powdered. Steel balls and either steel- or zirconia-lined canisters were used during milling.

Ashing was completed in a Carbolite laboratory chamber furnace with a Gero 301 PID controller, which allowed for a single ramp rate to a set temperature. This required a modification of the standard coal ashing procedure, which uses stepped temperature increases (Bullock and others, 2002; ASTM D7582-15, 2015). Samples were ashed in the furnace using a temperature ramp rate of 1°C (1.8°F) per minute up to 525°C (977°F), at which the furnace stayed for 32.5 hours. Samples were allowed to cool to room temperature before being removed from the furnace. Sample weights measured before and after combustion were used to determine ash content. Two samples (coal clinker, sample K-26-01; sandstone, sample K-27-05) were not ashed due to their visibly low organic content. All other samples, which were coals or coaly to carbonaceous shales and siltstones, were ashed. Between all steps, sample powders were stored in a desiccator to prevent rehydration.

Powdered and ashed samples were mixed with trace-metal grade lithium metaborate flux (Sigma-Aldrich product number 205524) at a 1:10 ratio in graphite crucibles for fusion into glass beads. The mixture was placed in a muffle furnace at 1,050°C (1,922°F) for 30 minutes, after which crucibles were removed from the furnace and the samples cooled. Beads were dissolved in 113-g (approximately 100 ml) 10 percent (V/V) trace-metal-grade nitric acid ($HNO_3$) in 125-ml bottles and placed on a shaker table for 10 hours. Sample solutions were diluted tenfold with deionized water due to high total dissolved solids from the lithium flux.

Major and minor elements were quantified by ICP-OES; trace elements and REEs were quantified by ICP-MS. Additional details about analytical methods are available in Appendix 2. The 39 elements targeted (fig. 4) were chosen based on three factors: (1) their presence on the USGS critical minerals list, (2) their known occurrence in other coal deposits at concentrations that are potentially economic (Dai and Finkelman, 2018), and (3) the ability of available instrumentation and preparation methods to efficiently and accurately quantify each element.
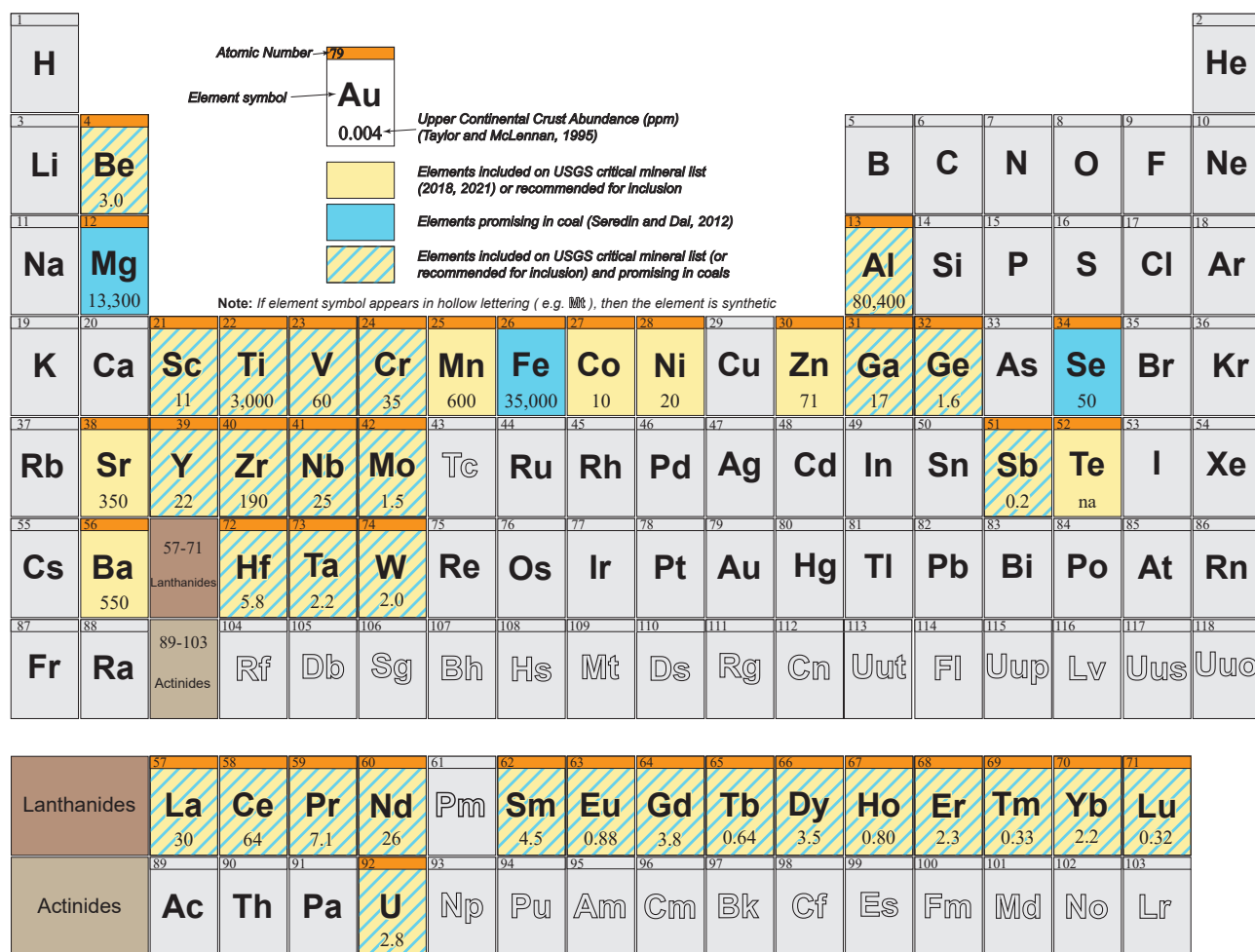


**Figure 4.** Periodic table highlighting the elements analyzed in this project, with all others grayed out. Of these analyzed elements, ones that are included on the USGS critical minerals list (U.S. Department of the Interior, 2018; Fortier and others, 2018; Nassar and Fortier, 2021) have a yellow background, and elements that may occur in coals at promising concentrations for production (Dai and Finkelman, 2018) have a blue background. Elements that are both on the USGS critical minerals list and considered promising in coals have a yellow and blue striped background.

## RESULTS AND DISCUSSION

### Ash Content

The variety of lithologies sampled and analyzed from these coal-bearing deposits had ash contents from 4.3 weight percent to 96.4 weight percent on a dry basis (Appendix 1). Samples were categorized by their ash content following ATSM International Standards (ASTM D121-15), where coals have 0–25 weight percent ash content and impure coals have 25–50 weight percent ash content. Samples with ash contents greater than 50 weight percent were categorized based on hand-sample descriptions—the majority are best described as carbonaceous shales, but samples of sandstone, clinker, and clay-rich partings were also included.

### Geochemistry

Elemental geochemistry for all samples is reported on a dry basis in parts per million (ppm). The complete dataset is available in Appendix 2. Subsequent sections highlight results for select elements: REEs, Ga, Ge, and tungsten (W).

Most elements measured in samples occurred at levels similar to or below their abundance in the upper continental crust, or UCC (Taylor and McLennan, 1995), with a few moderate exceptions. In coal samples, antimony (Sb) and W concentrations were elevated relative to UCC abundance, while carbonaceous shales had elevated amounts of chromium (Cr), Ge, molybdenum (Mo), Sb, erbium (Er), W, and U relative to UCC. Tellurium (Te) was not detected in any samples, indicating sample solutions were below the minimum detection limit (MDL) of 0.14 parts per billion (ppb) of the ICP-MS.

The concentration coefficient (Dai and others, 2015) compares the abundance of trace elements in coal and carbonaceous shale samples to global averages of coals and carbonaceous shales (Clarke values, from Ketris and Yudovich, 2009). The resulting value can be used to evaluate a sample's degree of enrichment in an element, ranging from depleted to unusually enriched (tables 1 and 2). The majority of elements occurred at levels considered "normal" or "depleted," except in coal samples where europium (Eu), holmium (Ho), tantalum (Ta), and Er were "slightly enriched" (one grade above "normal," where sample concentrations are two to five times higher than the global average) and W was "enriched" (sample concentrations are five to 10 times higher than the global average), while in carbonaceous shales beryllium (Be), Ge, praseodymium (Pr), Er, and Ta qualified as "slightly enriched."

**Table 1.** Coal concentration coefficients (CC) for all elements analyzed. CC is the relative enrichment of an element in coal samples to the average for global coals, and is determined using the method from Dai and others (2015).

| Element | Clarke value, global coals, (ppm)[1] | CC of all coal samples, averaged | Enrichment classification | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | > 100 Unusually enriched | 10 < CC < 100 Significantly enriched | 5 < CC < 10 Enriched | 2 < CC < 5 Slightly enriched | 0.5 < CC < 2 Normal | < 0.5 Depleted |
| Be | 1.6 | 1.5 | - | - | - | - | Y | - |
| Sc | 3.9 | 0.9 | - | - | - | - | Y | - |
| Ti | 800 | 0.7 | - | - | - | - | Y | - |
| V | 25 | 0.8 | - | - | - | - | Y | - |
| Cr | 16 | 2.0 | - | - | - | - | Y | - |
| Mn | 86 | 0.9 | - | - | - | - | Y | - |
| Co | 5.1 | 1.5 | - | - | - | - | Y | - |
| Ni | 13 | 1.6 | - | - | - | - | Y | - |
| Cu | 16 | 0.5 | - | - | - | - | - | Y |
| Zn | 23 | 1.3 | - | - | - | - | Y | - |

**Table 1.** continued

| Element | Clarke value, global coals, (ppm)[1] | CC of all coal samples, averaged | Enrichment classification | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | > 100 Unusually enriched | 10 < CC < 100 Significantly enriched | 5 < CC < 10 Enriched | 2 < CC < 5 Slightly enriched | 0.5 < CC < 2 Normal | < 0.5 Depleted |
| Ga | 5.8 | 1.0 | - | - | - | - | Y | - |
| Ge | 2.2 | 1.0 | - | - | - | - | Y | - |
| Sr | 110 | 1.2 | - | - | - | - | Y | - |
| Y | 8.4 | 1.6 | - | - | - | - | Y | - |
| Zr | 36 | 0.8 | - | - | - | - | Y | - |
| Nb | 3.7 | 0.9 | - | - | - | - | Y | - |
| Mo | 2.2 | 1.0 | - | - | - | - | Y | - |
| Sb | 0.92 | 0.8 | - | - | - | - | Y | - |
| Ba | 150 | 1.8 | - | - | - | - | Y | - |
| La | 11 | 0.8 | - | - | - | - | Y | - |
| Ce | 23 | 0.7 | - | - | - | - | Y | - |
| Pr | 3.5 | 0.6 | - | - | - | - | Y | - |
| Nd | 12 | 0.7 | - | - | - | - | Y | - |
| Sm | 2 | 1.0 | - | - | - | - | Y | - |
| Eu | 0.47 | 2.3 | - | - | - | Y | - | - |
| Gd | 2.7 | 0.8 | - | - | - | - | Y | - |
| Tb | 0.32 | 0.8 | - | - | - | - | Y | - |
| Dy | 2.1 | 0.9 | - | - | - | - | Y | - |
| Ho | 0.54 | 2.5 | - | - | - | Y | - | - |
| Er | 0.93 | 2.1 | - | - | - | Y | - | - |
| Tm | 0.31 | 0.8 | - | - | - | - | Y | - |
| Yb | 1 | 1.1 | - | - | - | - | Y | - |
| Lu | 0.2 | 1.4 | - | - | - | - | Y | - |
| Hf | 1.2 | 1.0 | - | - | - | - | Y | - |
| Ta | 0.28 | 2.2 | - | - | - | Y | - | - |
| W | 1.1 | 5.4 | - | - | Y | - | - | - |
| U | 2.4 | 0.7 | - | - | - | - | Y | - |

[1] from Ketris and Yudovich, 2009

**Table 2.** Carbonaceous shale concentration coefficients (CC) for all elements analyzed. CC is the relative enrichment of an element in carbonaceous shale samples to the average for global shales, and is determined using the method from Dai and others (2015). The concentration coefficient is unavailable for elements that were below the minimum detection limit (MDL).

| Element | Clarke value, all global carbonaceous shales (ppm)[1] | CC of all carbonaceous shale samples, averaged | Enrichment classification | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | > 100 Unusually enriched | 10 < CC < 100 Significantly enriched | 5 < CC < 10 Enriched | 2 < CC < 5 Slightly enriched | 0.5 < CC < 2 Normal | < 0.5 Depleted |
| Be | 2.1 | 2.3 | - | - | - | Y | - | - |
| Sc | 11 | 1.0 | - | - | - | - | Y | - |
| Ti | 2700 | 1.0 | - | - | - | - | Y | - |
| V | 180 | 0.6 | - | - | - | - | Y | - |
| Cr | 81 | 1.7 | - | - | - | - | Y | - |
| Mn | 440 | 0.1 | - | - | - | - | - | Y |
| Co | 14 | 0.4 | - | - | - | - | - | Y |
| Ni | 67 | 0.5 | - | - | - | - | Y | - |
| Cu | 87 | 0.2 | - | - | - | - | - | Y |
| Zn | 140 | 0.4 | - | - | - | - | - | Y |
| Ga | 17 | 1.4 | - | - | - | - | Y | - |
| Ge | 2.4 | 2.3 | - | - | - | Y | - | - |
| Sr | 290 | 0.4 | - | - | - | - | - | Y |
| Y | 23 | 1.0 | - | - | - | - | Y | - |
| Zr | 120 | 1.3 | - | - | - | - | Y | - |
| Nb | 10 | 1.5 | - | - | - | - | Y | - |
| Mo | 20 | 0.3 | - | - | - | - | - | Y |
| Sb | 5.6 | 0.3 | - | - | - | - | - | Y |
| Te | 2.1 | <MDL | | | | | | |
| Ba | 590 | 1.0 | - | - | - | - | Y | - |
| La | 28 | 1.6 | - | - | - | - | Y | - |
| Ce | 58 | 1.4 | - | - | - | - | Y | - |
| Pr | 4.3 | 2.2 | - | - | - | Y | - | - |
| Nd | 26 | 1.3 | - | - | - | - | Y | - |
| Sm | 4.6 | 1.4 | - | - | - | - | Y | - |
| Eu | 1 | < MDL | | | | | | |
| Gd | 3.8 | 1.5 | - | - | - | - | Y | - |
| Tb | 0.6 | 0.8 | - | - | - | - | Y | - |
| Dy | 2.7 | 1.7 | - | - | - | - | Y | - |
| Ho | 0.38 | < MDL | | | | | | |
| Er | 1.6 | 3.1 | - | - | - | Y | - | - |
| Tm | 0.26 | 1.9 | - | - | - | - | Y | - |
| Yb | 2.6 | 1.0 | - | - | - | - | Y | - |
| Lu | 0.35 | 1.8 | - | - | - | - | Y | - |
| Hf | 3.5 | 1.5 | - | - | - | - | Y | - |
| Ta | 0.66 | 2.5 | - | - | - | Y | - | - |
| W | 7.8 | 1.2 | - | - | - | - | Y | - |
| U | 13 | 0.5 | - | - | - | - | Y | - |

[1] from Ketris and Yudovich, 2009

*Rare Earth Elements*

The elements considered REEs, and how they are discussed, varies from publication to publication. While Sc and Y are often considered REEs due to their association with the lanthanide series elements in natural deposits and similar chemical properties, the inclusion of these elements in REE datasets is inconsistent. In this section we discuss Sc and Y concentrations individually and the lanthanide series elements together as a single sum (table 3), although concentrations for each lanthanide element are reported in Appendix 2.

Table 3 summarizes the Sc, Y, and total lanthanides results by formation and sample composition. The total concentration of lanthanide series elements in samples (TLa; equal to the sum of all 14 naturally occurring lanthanide elements) ranges from less than 1 ppm to more than 610 ppm on a dry basis. Sc and Y have concentrations from less than 1 to 31 and 64 ppm, respectively. TLa, Sc, and Y concentrations varied depending on sample composition and ash content, but were consistent for similar compositions across the two formations (fig. 5). Eu and Ho measurements (Appendix 2) were below the MDL for all carbonaceous shales and a majority of coals, so the averages reported here for these two elements are not necessarily representative of all samples.

**Table 3.** Summary of Sc, Y, and TLa results, reported by formation and sample type, in ppm and on a whole, dry basis. Adaville Formation is abbreviated Kav. Frontier Formation is abbreviated Kf.

| Sample group | Number of samples (n) | Sc | | | Y | | | TLa | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Range (ppm) | | Average (ppm) | Range (ppm) | | Average (ppm) | Range (ppm) | | Average (ppm) |
| | | Min. | Max. | | Min. | Max. | | Min. | Max. | |
| Kav, coal tipple samples | 7 | 0.05 | 1.46 | 0.64 | 0.14 | 4.00 | 1.72 | 0.75 | 26.36 | 10.49 |
| Kav, coal samples from outcrop | 14 | 0.24 | 12.54 | 5.06 | 0.97 | 64.71 | 18.63 | 3.46 | 227.77 | 58.56 |
| Kav, carbonaceous shale samples from outcrop | 14 | 5.40 | 24.76 | 9.98 | 13.00 | 37.96 | 22.99 | 87.80 | 287.14 | 166.67 |
| Kav, parting samples from outcrops | 2 | 1.28 | 1.92 | 1.60 | 4.33 | 7.75 | 6.04 | 84.99 | 204.49 | 144.74 |
| Kf, coal samples from outcrop | 12 | 1.20 | 8.65 | 3.26 | 2.98 | 39.03 | 13.75 | 14.35 | 116.40 | 43.85 |
| Kf, carbonaceous shale samples from outcrop | 13 | 4.68 | 24.75 | 13.14 | 9.69 | 51.70 | 23.05 | 23.00 | 612.15 | 208.71 |

*Single samples from Kav clinker and Kf sandstone not included in summary*

Adaville Formation coals collected from outcrops averaged 58 ppm TLa, 5 ppm Sc, and 18 ppm Y. Pulverized coal samples collected from the conveyor system at the Kemmerer Mine had lower values, averaging 10 ppm TLa, less than 1 ppm Sc, and less than 2 ppm Y. Carbonaceous shales collected from the Adaville Formation averaged 166 ppm TLa, 10 ppm Sc, and 23 ppm Y. Two clay-rich partings collected from the Adaville 365 seam had 85 and 204 ppm TLa, 1 and 2 ppm Sc, and 4 and 7 ppm Y. A sample of clinker collected from a waste pile within the Kemmerer Mine had the highest Sc and Y concentrations of all samples measured, 31 and 61 ppm, respectively, and a TLa concentration of 266 ppm.

The carbonaceous shales sampled from the Frontier Formation averaged 208 ppm TLa, 13 ppm Sc, and 23 ppm Y. Frontier Formation coals averaged 44 ppm TLa, 3 ppm Sc, and 13 ppm Y. The greatest TLa concentration was measured in a grab sample of a carbonaceous shale with TLa of 612 ppm.

Overall, individual lanthanide, Sc, and Y concentrations of samples were similar to abundances in the UCC (Taylor and McLennan, 1995). All coal samples and most carbonaceous shales had concentrations of lanthanide elements, Sc, and Y that were close to or less than abundances in the UCC (fig. 6). However, carbonaceous shales were moderately elevated in Er and Lu (Appendix 2), averaging about twice the abundance of each element in the UCC.
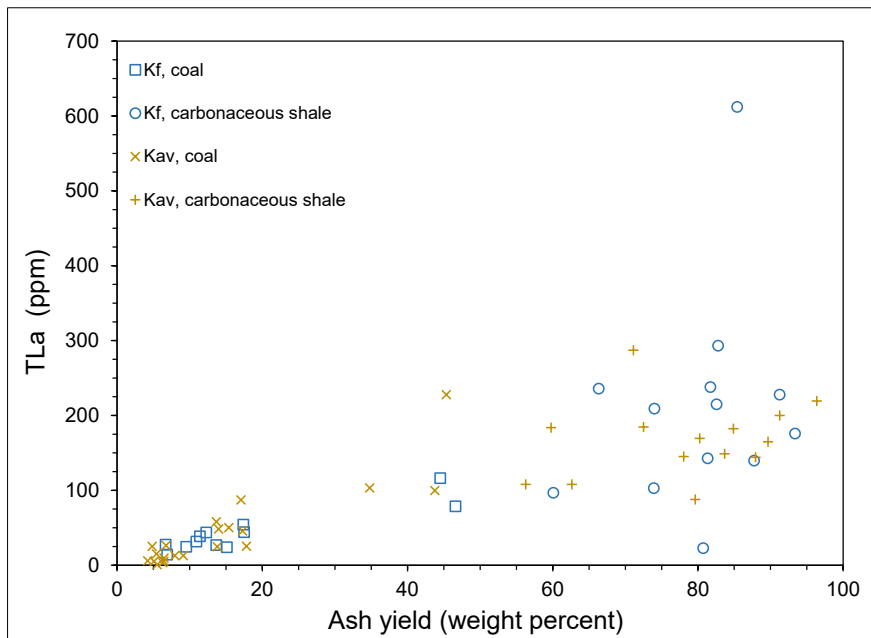


**Figure 5.** Plot of total lanthanides (TLa; ppm) versus ash content (weight percent) of samples. Coal and carbonaceous shale samples form relatively distinct populations. There is a general trend of increasing TLa with increased ash content.
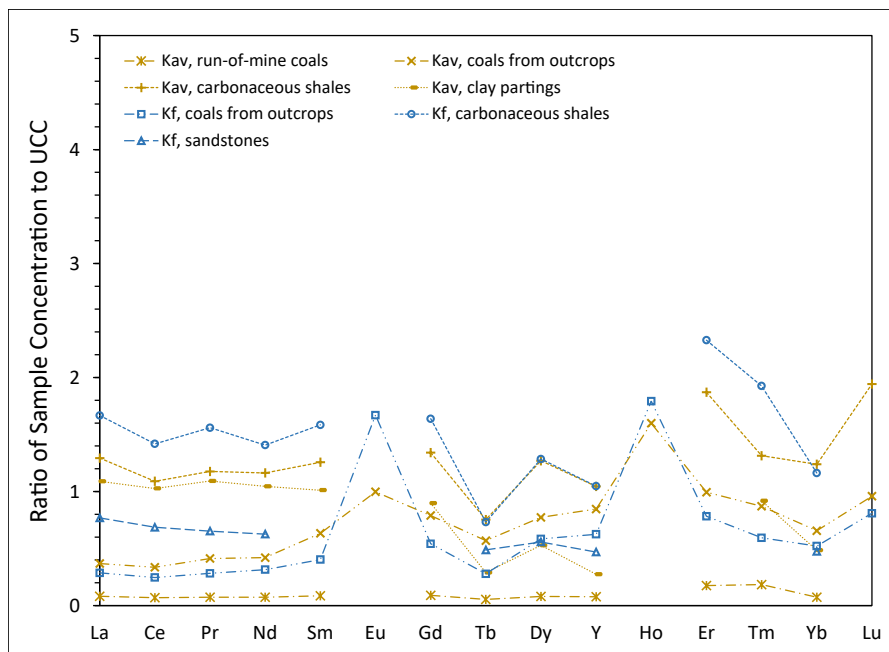


**Figure 6.** Distribution patterns of lanthanides and yttrium for averages of sample lithologies. Element concentrations are normalized by their average abundance in the upper continental crust (UCC; Taylor and McLennan, 1985). Gaps in the data indicate value(s) were below the minimum detection limit of the instrument.

Based on concentration coefficients (Dai and others, 2015), coals sampled from the Kemmerer and Adaville formations on average have normal to depleted levels of Sc, Y, and most lanthanides, although Eu and Ho, when detected at concentrations above the MDL, also occurred at slightly enriched levels, as did Er (table 1). For the carbonaceous shales sampled from both formations, the concentration coefficient can be determined using the averages of global carbonaceous shales (Ketris and Yudovich, 2009; Mastalerz and others, 2020). These samples have concentration coefficients indicating slight enrichment in Pr and Er, and normal levels of all other lanthanides, Sc, and Y (table 2).

*Gallium*

Ga concentrations range from less than one ppm to 62 ppm on a dry basis (table 4). On average, carbonaceous shales had higher concentrations than associated coals.

Samples of Adaville Formation coals collected from outcrop had an average Ga concentration of 9 ppm, while pulverized coals sampled from the conveyor system averaged 1 ppm. Carbonaceous shales collected from the Adaville Formation averaged 20 ppm, and the two clay-rich partings contained 12 and 35 ppm Ga. Frontier Formation coals averaged 4 ppm Ga, and carbonaceous shales averaged 29 ppm.

Ga concentrations of both coals and carbonaceous shales are within the "normal" enrichment category (tables 1 and 2) based on the average concentration coefficients (Dai and others, 2015), and concentrations are not enriched relative to the UCC abundance of Ga.

**Table 4.** Summary of Ga, Ge, and W results, reported by formation and sample type, in ppm and on a whole, dry basis. Adaville Formation is abbreviated Kav. Frontier Formation is abbreviated Kf.

| Sample group | Number of samples (n) | Ga Range (ppm) Min. | Ga Range (ppm) Max. | Ga Average (ppm) | Ge Range (ppm) Min. | Ge Range (ppm) Max. | Ge Average (ppm) | W Range (ppm) Min. | W Range (ppm) Max. | W Average (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| Kav, coal tipple samples | 7 | 0.10 | 3.57 | 1.42 | 0.03 | 6.54 | 1.21 | 0.13 | 2.63 | 1.27 |
| Kav, coal samples from outcrop | 14 | 0.29 | 27.40 | 9.17 | 0.25 | 7.93 | 2.65 | 1.16 | 99.33 | 10.06 |
| Kav, carbonaceous shale samples from outcrop | 14 | 8.93 | 45.49 | 20.21 | 2.10 | 9.50 | 4.53 | 1.81 | 30.75 | 13.19 |
| Kav, parting samples from outcrops | 2 | 12.30 | 35.14 | 23.72 | 1.23 | 4.54 | 2.88 | 1.40 | 17.61 | 9.50 |
| Kf, coal samples from outcrop | 12 | 1.30 | 14.65 | 4.85 | 0.80 | 7.00 | 2.12 | 0.85 | 7.13 | 3.24 |
| Kf, carbonaceous shale samples from outcrop | 13 | 15.79 | 62.90 | 29.22 | 2.54 | 12.07 | 6.43 | 2.99 | 12.78 | 6.03 |

*Single samples from Kav clinker and Kf sandstone not included in summary*

*Germanium*

Samples in this study contained Ge concentrations from less than 1 ppm to 26 ppm on a dry basis, averaging 4 ppm (table 4).

Samples from the Adaville Formation had average Ge concentrations of 2 ppm in coals sampled from outcrops, 1 ppm in pulverized coals, 4 ppm in carbonaceous shales, and the two clay-rich partings yielded 1 and 4 ppm. In the Frontier Formation, coal sampled from outcrops had an average concentration of 2 ppm while carbonaceous shales averaged 6 ppm.

Ge content in carbonaceous shale samples are "slightly enriched" relative to global black shales (table 2), and averaged more than three times UCC abundance. In coal samples, Ge concentrations are within "normal" range of global coals (table 1) and are similar to UCC abundance.

*Tungsten*

Samples had W concentrations from less than 1 ppm to 119 ppm (table 4). Concentrations in Adaville Formation samples are higher than for those from the Frontier Formation.

Frontier Formation coals sampled from outcrops averaged 3 ppm W, and carbonaceous shales averaged 6 ppm W. In the Adaville Formation, the tipple coal samples had an average concentration of 1 ppm, while the other Adaville coals averaged 10 ppm. In the two clay-rich partings W was measured at 1 and 17 ppm; the carbonaceous shales averaged 13 ppm.

A few samples have significantly higher W concentrations than the rest. While this skews average W concentrations, these outliers occur at concentrations that suggest the importance of further investigation. The highest W concentration, at 119 ppm, was measured in a Frontier Formation grab sample of a medium-grained litharenite with abundant woody fragments (sample KC-KK-082720-05). One coal sample (KC-KK-082620-04c) had 99 ppm W, which contributed to an average W concentration coefficient for coal samples of 5.4 ppm, indicating these coals are "enriched" relative to global coals (table 1). If this value is excluded from the average concentration coefficient of coal samples, then the value decreases to 2.9, which qualifies as "slightly enriched" relative to global coals. This anomalous W value was collected from the middle of a 4-m-thick (12 ft) coal bed (transect KK-082620-04); samples collected from other vertical locations within the coal bed had significantly lower concentrations, between 2 to 6 ppm, and samples from the bounding roof and floor rocks contained 5–30 ppm W.

## CONCLUSIONS

This study quantifies the trace element composition of samples collected from specific stratigraphic positions within coal-bearing and associated strata in the Adaville and Frontier formations. It provides more geochemical data about the Kemmerer coal field in order to improve our understanding of trace-element occurrences in these deposits, but it is by no means a complete evaluation of the critical mineral potential of the coal field.

Overall, samples contain concentrations of the analyzed elements at levels considered "normal" or "depleted" relative to the average concentrations in coals and carbonaceous shales around the world. In coal samples, the outliers were Eu, Ho, Er, and Ta, which were "slightly enriched," and W, which was "enriched," although that was due to a single anomalous sample. In carbonaceous shales the elements Be, Ge, Pr, Er, and Ta qualified as "slightly enriched" relative to global averages.

Of the elements discussed in further depth (Sc, Y, TLa, Ga, Ge, W), a few trends are worth highlighting. Typically, the carbonaceous shales from both units have significantly higher TLa content than the coals, though this dataset is not large enough to reveal any trends indicating if over- or underlying shales are more enriched relative to each other. In the Adaville Formation, the middle of the coal beds have lower TLa concentrations than the parts of the coal closer to the over and underlying rocks (table 5). Samples from transects in the Frontier Formation show higher TLa concentrations near the base of the coal bed than in the middle to upper parts of the coals. Ga, Sc, and Y are elevated in carbonaceous shales relative to coals in both units, but distributions of Ge and W are fairly even between different lithologies.

Comparing samples between the two formations, Ga occurs at higher concentrations in carbonaceous shales in the Frontier than in the Adaville Formation, while concentrations are similar in coals across the two formations.

W concentrations are generally higher in the Adaville Formation than in the Frontier Formation; besides the single coal sample with an anomalously high amount, carbonaceous shales in the Adaville are also enriched in W relative to those in the Frontier.

**Table 5.** Summary of results for Sc, Y, TLa, Ga, Ge, and W, as averaged by formation and vertical position, in ppm and on a whole, dry-basis. Adaville Formation is abbreviated Kav. Frontier Formation is abbreviated Kf.

| Sample group | Number of samples (n) | Sc (ppm) | Y (ppm) | TLa (ppm) | Ga (ppm) | Ge (ppm) | W (ppm) |
|---|---|---|---|---|---|---|---|
| Kav, roof rock | 3 | 10.61 | 21.27 | 138.95 | 19.75 | 4.74 | 4.93 |
| Kav, coal, upper section | 2 | 7.49 | 24.84 | 41.64 | 7.69 | 4.91 | 2.25 |
| Kav, coal, middle of bed | 2 | 2.21 | 10.49 | 26.96 | 3.08 | 0.94 | 50.96 |
| Kav, coal, lower section | 7 | 4.50 | 15.11 | 43.71 | 7.77 | 2.41 | 3.71 |
| Kav, floor rock | 9 | 10.26 | 23.50 | 180.68 | 21.35 | 4.61 | 15.64 |
| Kf, roof rock | 2 | 14.21 | 23.12 | 231.92 | 28.57 | 6.90 | 4.02 |
| Kf, coal, upper section | 4 | 2.01 | 7.30 | 35.31 | 3.48 | 1.38 | 3.34 |
| Kf, coal, middle of bed | 3 | 3.31 | 14.24 | 37.67 | 4.22 | 1.81 | 2.98 |
| Kf, coal, lower section | 5 | 4.24 | 18.63 | 54.38 | 6.31 | 2.89 | 3.32 |
| Kf, floor rock | 7 | 13.10 | 21.60 | 168.87 | 27.53 | 6.20 | 5.55 |

The tipple samples from the Kemmerer Mine had concentrations similar to or lower than samples collected from the same beds in outcrop; the biggest discrepancies were between the tipple samples and coals sampled closest to the contacts with roof and floor rocks. This is expected, since the mining method excludes the top and bottom margins of the coal bed from mined product, eliminating the parts of the coal seam that tend to be enriched in REEs. This also suggests that the mine's waste rock may host a larger volume of REEs than the coal itself. However, it is uncertain how the waste rock would compare to concentrations of coal byproducts such as combustion fly ash.

Additional research would be required in order to better understand element distribution and critical mineral associations in these coal-bearing formations. Analyzing core samples from multiple coals and bounding beds would provide finer resolution of variations in element distribution, and a larger sample size would allow for a better understanding of trends in distribution and enrichment. Multiple approaches could help unravel the factors influencing trace-element occurrence: detailed mineralogical and stratigraphic studies of the bounding beds could identify if elevated concentrations are associated with specific lithofacies, and studying the distribution trends of trace elements would illuminate modes of enrichment, contributing to better understanding of the depositional and post-depositional histories of these two formations.

Characterizing the trace-element chemistry of specific geologic deposits contributes to a better understanding of where to direct future efforts in developing domestic sources of critical minerals. Knowledge of these potential sources ensures efficient adaptation to changes in the critical minerals market, whether by engineering technologies or economic conditions.

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# Appendices

# Appendix 1. Sample details and locations

**Table A1–1.**   Sample name, location, and details for samples collected from the Kemmerer coal field for this project. Samples are from the Adaville Formation (Kav) or the Frontier Formation (Kf). This table is available from the Wyoming State Geological Survey (www.wsgs.wyo.gov), where it can be downloaded in conjunction with a pdf of this report.

# Appendix 2. Geochemical data

**Table A2–1.**   Geochemical results for all samples plus NIST Standard Reference Material 1635a. Reported on a dry-basis in ppm or weight percent. All samples were analyzed once with the ICP-OES, and one or more times with the ICP-MS. Results of each analysis from all batch runs are reported here, including multiple ash yields if a sample was ashed multiple times. MDLs reported for each element at bottom of table in ppb. National Institute of Standards and Technology SRM 1635a, for trace elements in coal, was prepared and analyzed alongside the samples using the same methods. This table is available from the Wyoming State Geological Survey (www.wsgs.wyo.gov), where it can be downloaded in conjunction with a pdf of this report.

Major and minor elements were analyzed by inductively coupled plasma optical emission spectrometry using a Perkin-Elmer Optima 8300 ICP-OES. All standards were prepared from certified materials (Inorganic Ventures, Christianburg, VA). A minimum of five levels of calibration were used. Standards were measured for quality control after calibration, in the middle of, and at the end of each run. MDLs were calculated using the standard deviation of seven replicates of a non-zero (1 ppb) standard multiplied by the T-statistic for 6 degrees of freedom and a 99% confidence interval.

Trace elements, including rare earth elements, were analyzed by inductively coupled plasma mass spectrometry using a ThermoFischer iCAP single quadrupole ICP-MS. All standards were prepared from certified materials (Inorganic Ventures, Christianburg, VA). Indium and bismuth were used as internal standards. A minimum of five levels of calibration were used. Standards were measured for quality control at the beginning and end of each run, and occasionally in the middle if a run included a larger number of samples. Some ICP-MS runs did not include a standard for terbium (Tb); the resulting Tb measurements could not be quantified, and are marked with *NQ*. MDLs were calculated using the standard deviation of five replicates of a non-zero (2.5 ppb) standard multiplied by the T-statistic for 4 degrees of freedom and a 99% confidence interval.