Montana Bureau of Mines and Geology
Miscellaneous Contribution 77

Montana Bureau of Mines and Geology Project Summaries: Materials Technology for Rare Earth Elements Processing (MT-REEP)—Army Research Lab

January 2025
Adrian Van Rythoven, Ted Duaime, and Ryan Davison

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MT-REEP Task 3—Rare Earth Element Investigation of the Phosphoria Formation in Southwestern Montana

Executive Summary **January 2025**

Task Lead: Adrian Van Rythoven

Introduction

This task aims to assess the rare earth element (REE) potential in mine waste (and unmined remaining rock) from the Phosphoria Formation in southwestern Montana. Other critical minerals such as vanadium, chromium, zinc, and nickel are also considered.

During the 1900s, the Phosphoria Formation in Montana was a significant producer of phosphate. Currently, there is no active phosphate mining in Montana. However, the same formation is currently mined at multiple locations in Idaho and Utah. Phosphate-bearing (and critical-mineral-bearing) wastes and unmined rock remain at dozens of former mine sites in Montana.

Objectives

The Task's goal is the assessment of Phosphoria-related entities in Montana for critical minerals (primarily REEs, but also V, Cr, etc.). Most of the targeted entities are former small phosphate mines that range from abandoned to completely reclaimed. These assessments incorporate reconnaissance mapping, sampling, stratigraphic profiling, and field measurements (structural, geophysical, and geochemical). Sampled materials at these entities include tailings, waste rock, slag, leach residues, trenched material, and rock outcrops. These samples are then processed into representative splits for assay, thin section, and archival samples. Thin sections are used to collect mineralogical and textural information about the mineral deposit that complements the chemical assay data. Stratigraphic profiling for the rare sites where *in situ* strata occur provides spatial context for the beds in the Phosphoria Formation with the REE and other critical mineral enrichment.

These collected data provide an understanding of the nature of mineralization in the deposit. This allows for a preliminary, but comprehensive, assessment of the feasibility of critical mineral extraction at each entity. Based on this reconnaissance work, the assessed entities can be ranked not only in terms of contained critical minerals, but by the feasibility of their production.

Activities July 2022 to December 2024

A total of 133 samples were collected across 18 different entities (localities) from 5 counties in southwestern Montana (fig. 1). Two of these entities have intact exposed strata from which a stratigraphic section was measured. An additional 33 core samples were obtained from a V-REE-P exploration project in southwestern Idaho.

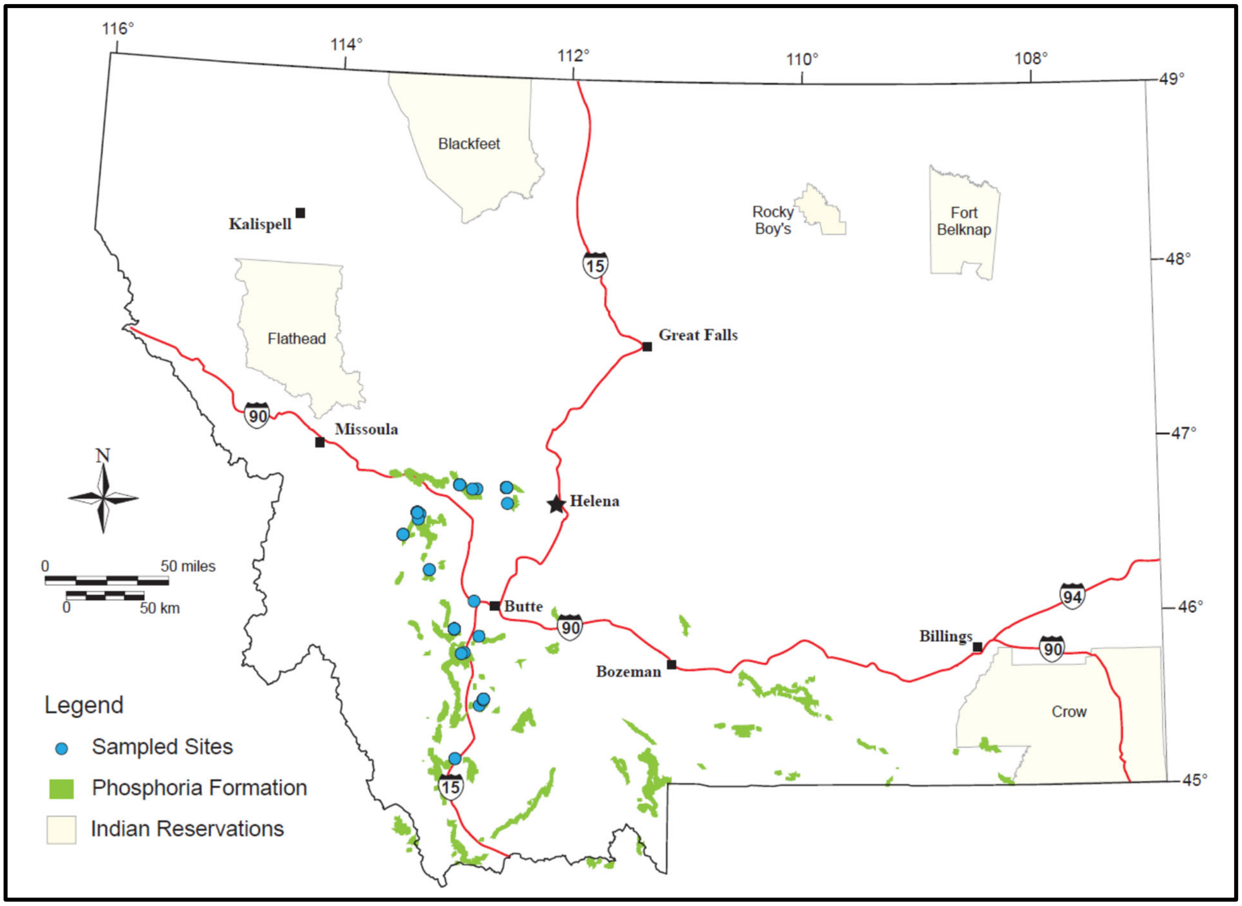

Figure 1. Extent of Phosphoria Formation in Montana (green), and sampled entities (teal).

The samples were assayed for 66 different analytes across five different methods by ALS Global using analytical package CCP-PKG01.

To characterize the microscopic textures of the samples, representative rock sample splits were mounted on a glass slide as a polished thin section for optical microscopy analysis in reflected and transmitted light. Mineralogical characterization was completed by automated mineralogical analysis using a scanning electron microscope. These data allow for detailed assessment of the rock's economic potential with an aim to extract the mineral resource(s).

It has been found that the REE content of the Formation is variable and does not strongly correlate with phosphate grade. One supported M.S. student, Nicholas Risedorf, is working to determine indicators for high REE mineralization in the Formation. In cases where sampling was done on *in situ* sedimentary strata, a stratigraphic section was created to model the variations in grades and geology with spatial context. Modeling these trends across different localities allow for interpolation of resources in unexplored areas.

To move beyond exploration and resource evaluation, a senior Metallurgical Engineering Design student, Taylor Nielsen, is funded to conduct bench-scale experiments on mixed Phosphoria mine waste from the Edgar Mine. The goal of this supported project is to create a physical processing flowsheet for optimal comminution and beneficiation.

Notable Results

Rare Earth Elements: The results to date show total elemental REE grades in phosphorite from the Phosphoria Formation in Montana that are as high as 0.35 wt.%. Most phosphorite in the formation ranges between 0.1 and 0.3 wt.%. REE distribution is consistent. Typically, 45% to 50% of the REE grade (including Y) is Tb or heavier. The grades for heavy REEs are comparable or superior to most commercial REE mines or mines in development (fig. 2).

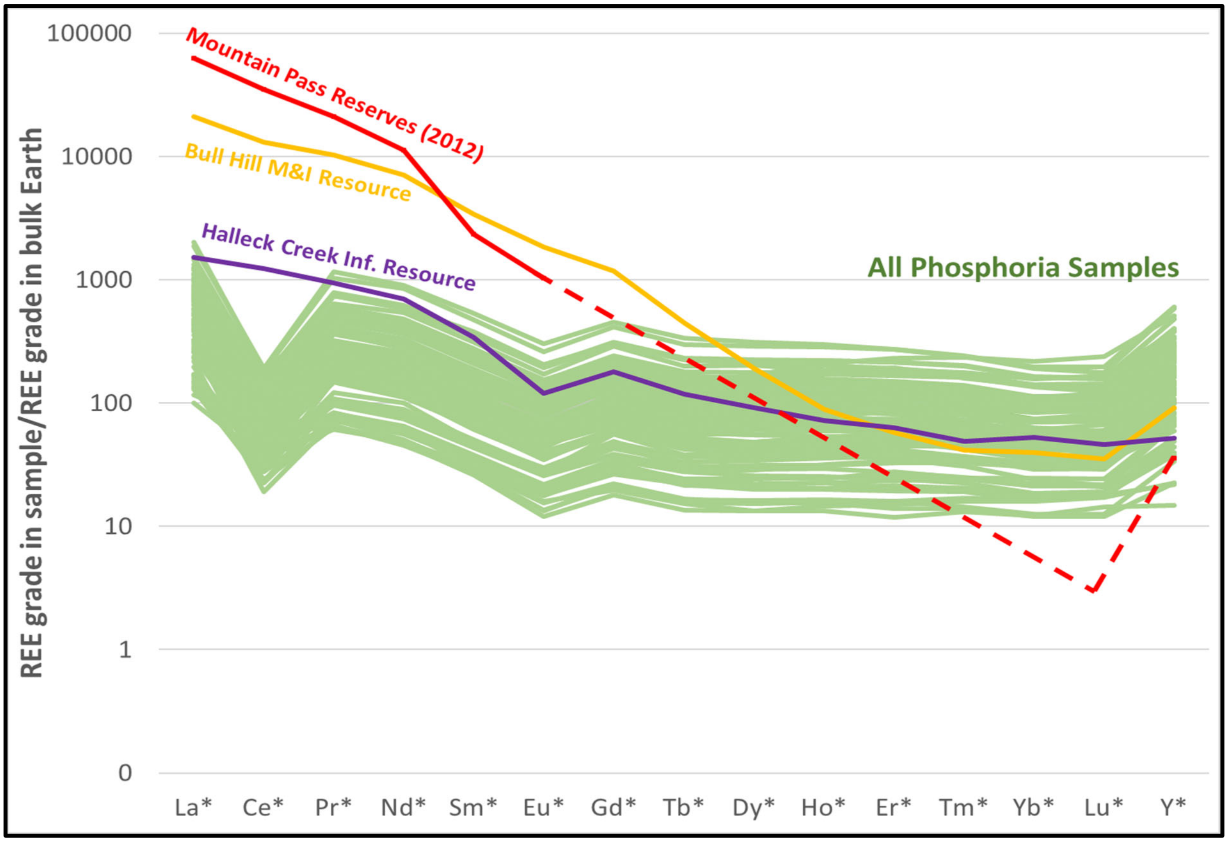

Figure 2. A chondrite-normalized plot of normalized REE concentrations from the Phosphoria Formation samples in this study. Also shown are values for established REE mines or developing mines. Chondrite-normalized plots essentially show an "enrichment factor" of concentration for each individual REE on one diagram, allowing for easier comparison.

Other Critical Minerals: Shale-rich, phosphorite-poor beds in the Formation can have notable V content, up to 0.75 wt.%. These beds can also have other high levels of critical minerals: Cr (<0.3 wt.%), Zn (<1.4 wt.%), and Ni (<0.1 wt.%).

Other Commodities: Phosphorous content in the formation ranges from negligible in chert-rich beds to 38 wt.% P_2O_5 in the highest grade phosphorite. Uranium is anomalously high in the phosphatic beds of the formation (<0.015 wt.% U). Uranium positively correlates with phosphorous content and is a useful proxy to measure with gamma-ray spectrometry. The shale-rich beds are high in organic carbon as kerogen/bitumen.

Produced Publications

Van Rythoven, A.D., 2023, Preliminary data release of whole-rock assays from Phosphoria-related entities in southwest Montana: Montana Bureau of Mines and Geology Analytical Dataset 6, https://doi.org/10.59691/GEPA6042

Van Rythoven, A.D., 2024. Preliminary results of an investigation into the Phosphoria Formation of southwestern Montana for critical mineral potential: Montana Bureau of Mines and Geology Special Publication 124, 2023 Montana Mining and Mineral Symposium Proceedings, p. 73–84, https://doi.org/10.59691/TTSI4436

Planned Future Work

Additional sampling will be performed to develop a larger and more statistically meaningful dataset to determine mineralization trends in the formation. This will require 100–200 samples over the next 2.5 years. The focus will be on the southern and eastern extents of the formation (fig. 1).

Three other stratigraphic section sites, identified with the assistance of consultant Dr. Marc Hendrix, will be measured and sampled over the next two field seasons.

The resulting data from the five different sites can be correlated with each other and with similar sites measured in Idaho, Wyoming, and Utah, to achieve basin-scale estimates of the most mineralized beds.

The mine waste and stratigraphic section sample data (assays, petrography) will be used in Nicholas Risedorf's thesis into the nature of REE mineralization processes in the formation.

Results from Taylor Nielsen's design project will also inform development of a flowsheet for processing of phosphate mineral concentrate to produce not only a mixed REE oxide product, but also a phosphate product. Contact has been made with Itafos Inc., a company that currently mines the Formation for phosphate in Idaho, to assess the potential for commercial REE extraction as a byproduct.

MT-REEP Task 4—Identification and Characterization of Rare Earth Elements in Montana's Large-Scale Mine Wastes

Executive Summary January 2025

Task Lead: Ted Duaime

Introduction

This task aims to identify Rare Earth Element (REE) occurrences in large-scale waste sources associated with past underground and open-pit mining and ore processing facilities throughout Montana. Mine types include metallic, non-metallic, and coal. Programs to identify REE deposits throughout the U.S. are underway; however, exploration and mine development can take decades before an increase in U.S. resources and production is realized. Recovery of REEs from abandoned/inactive sites would shorten the time necessary to add to the U.S. REE supply and production, as no new mine permitting would be required. Recovery of REEs from mine waste has a secondary benefit of aiding environmental cleanup and reducing waste sources.

Objectives

Task 4 focuses on the collection of samples from a preliminary list of large-scale mining and ore processing sites throughout Montana. The list currently consists of 22 sites. Each site can have multiple waste sources and source areas, e.g., the Philipsburg Mining District, where 77 solid samples were collected from 17 different waste sources. Table 1 lists the targeted sites, while figure 1 shows the counties the sites are located within. Counties where samples were collected are identified on the map.

Table 1. Preliminary sites identified for reconnaissance sampling and analysis.

Butte Operations	Black Eagle Smelter–Great Falls
Anaconda Operations	Roundup/Red Lodge Coal Fields
Columbia Falls Aluminum Plant	Nye/Fishtail Chrome–PGM
Beal Mountain	Zortman–Landusky
Golden Sunlight Mine	Montana Tunnels
Solvay/Stauffer	Thompson Falls–U.S. Minerals
Garrison–Phosphate Area Mines	Kendall Mine–Lewistown
Philipsburg Mining District	Hog Heaven Mine–Kalispell Area
Basin/Ten Mile Watersheds	Carpenter–Snow Creek
Great Falls–Lewistown Coal	Flat Creek Tailings
Barkers–Hughesville	Mike Horse Mine

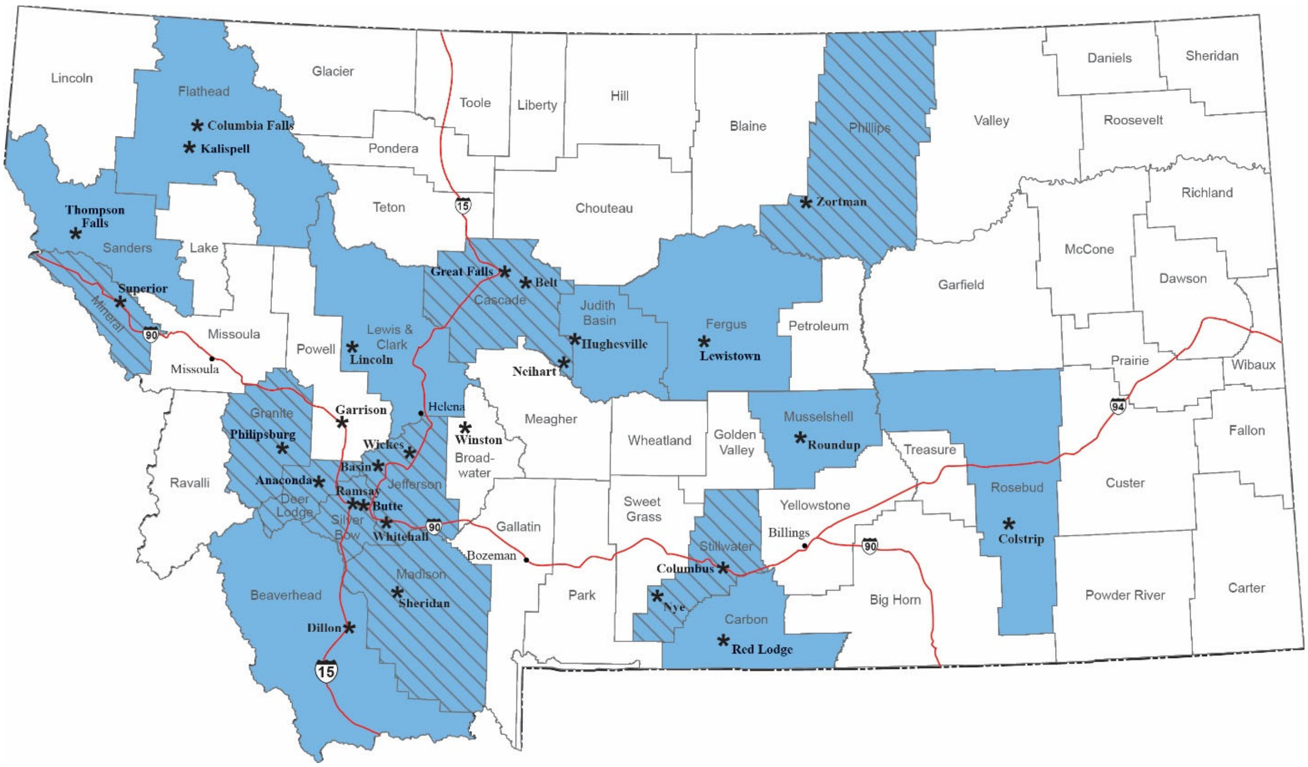

Figure 3. Location map showing counties where study/sampling areas are located throughout Montana. Hatched counties are those where REE samples were collected during year 1 activities.

Year 1 Activities

Year 1 work focused on the following activities:

1. Perform a thorough literature search of existing information for each site and compile REE data,
2. Develop detailed field and laboratory quality assurance project plans (QAPP) and sampling and analysis plans (SAP) to ensure high-quality data are collected and analytical data meet the ARL program goals,
3. Contact property owners and regulatory agencies (i.e., USFS, EPA, and MTDEQ) for site access, and
4. Implement a reconnaissance sampling program to collect opportunistic aqueous and solid samples for REE at sites located in southwest and south-central Montana.

Reconnaissance sampling was conducted during year 1 at easily accessible sites that had data suggesting the presence of REEs in waste material. The reconnaissance sampling entailed collecting an adequate number of solid and/or aqueous samples to determine if REE concentrations merit more detailed sampling. Sample sites included acid mine drainage discharge, sludge from water treatment facilities, waste dumps, smelter wastes, and mill tailings. Figure 2 is an example of an aqueous sample site. Samples were collected at 12 of the 22 sites (table 1), with a total of 392 samples collected.

Figure 4. Zortman-Landusky water treatment plant discharge, Phillips County.

The initial results are being used to develop more detailed sampling plans at sites with elevated REE concentrations. The benchmarks used to determine elevated REE concentrations are: 412 milligram per kilogram (mg/kg) in solids/sludge (concentration approximately two times that found in Earth's crust (206 mg/kg; Balaram, 2019); and total REE concentrations above 499 micrograms per liter (µg/L) in aqueous samples (value identified as having secondary recovery potential). Sites were also evaluated on the ratio of the amount of critical REEs (i.e., neodymium, europium, terbium, dysprosium, erbium, and yttrium) in the REE sum to the amount of more abundant REEs, also known as the outlook coefficient (Coutl; Seredin and Dai, 2011). The higher the coefficient, the more promising the material is as a secondary source; sites with a coefficient of 0.7 or above are considered elevated for critical REEs.

Results

In the first year, 12 of the 22 sites were visited, with almost 400 samples collected from various locations and waste sources. REEs were present in all of the samples collected; however, concentrations vary considerably between sites and waste sources. Figures 3 and 4 show average

REE concentrations for solid samples collected during year 1; figures 5 and 6 show average REE concentrations for aqueous samples collected during year 1.

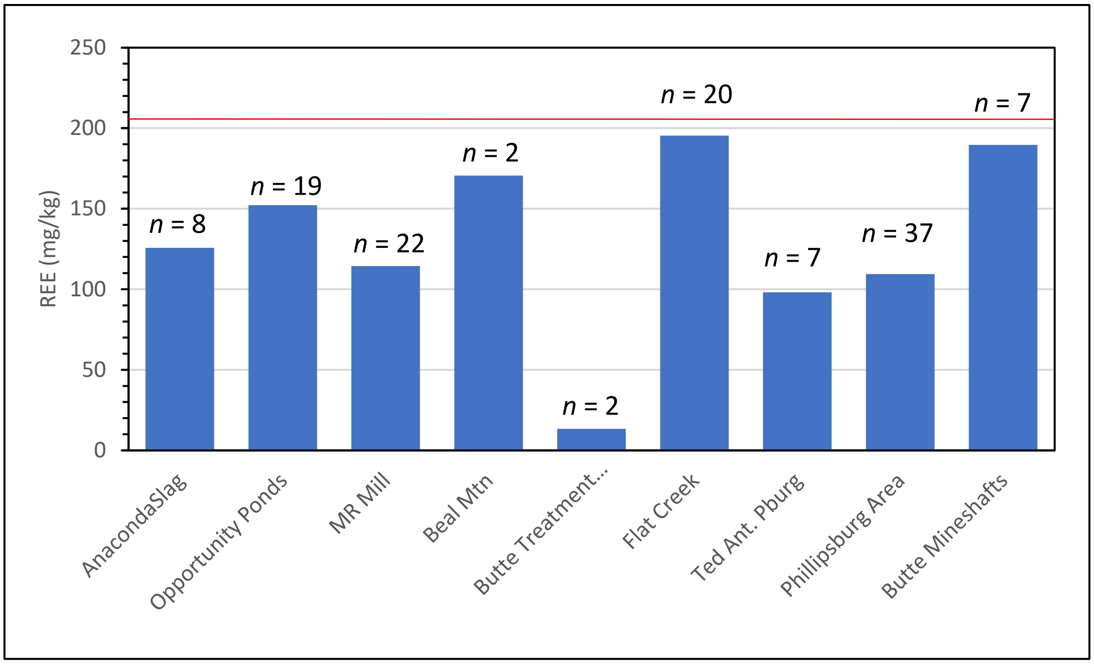

Figure 5. Average total REE concentrations per solid sample site for samples below 206 mg/kg. The red line represents the average REE concentration in Earth's crust, which is about 206 mg/kg.

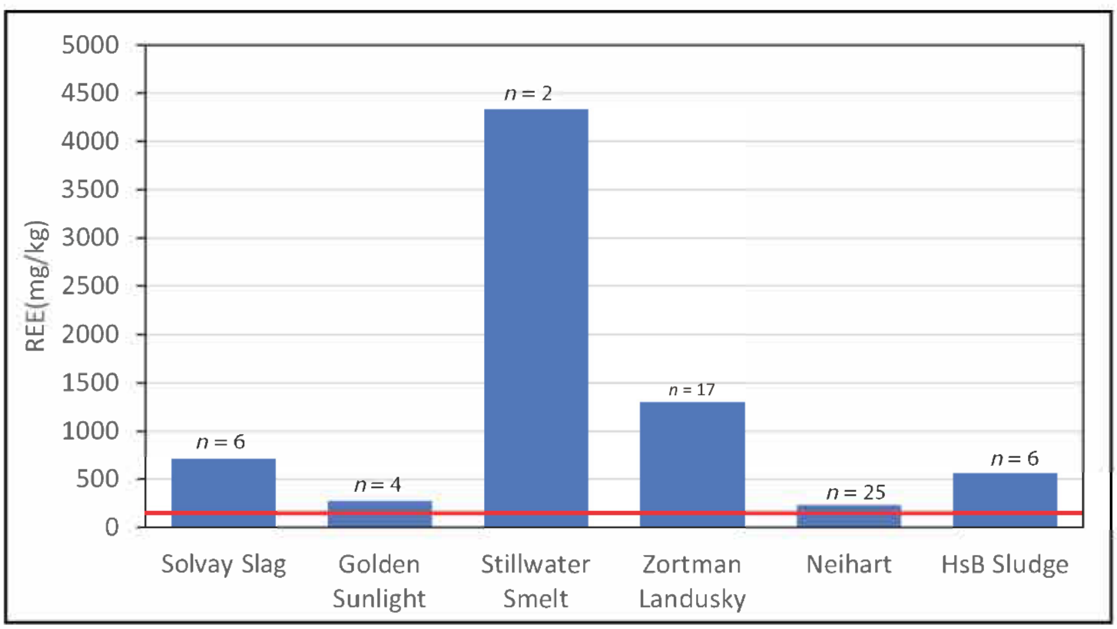

Figure 6. Average total REE concentrations per solid sample site for samples above 206 mg/kg. The red line represents the average REE concentration in the Earth's crust, which is about 206 mg/kg.

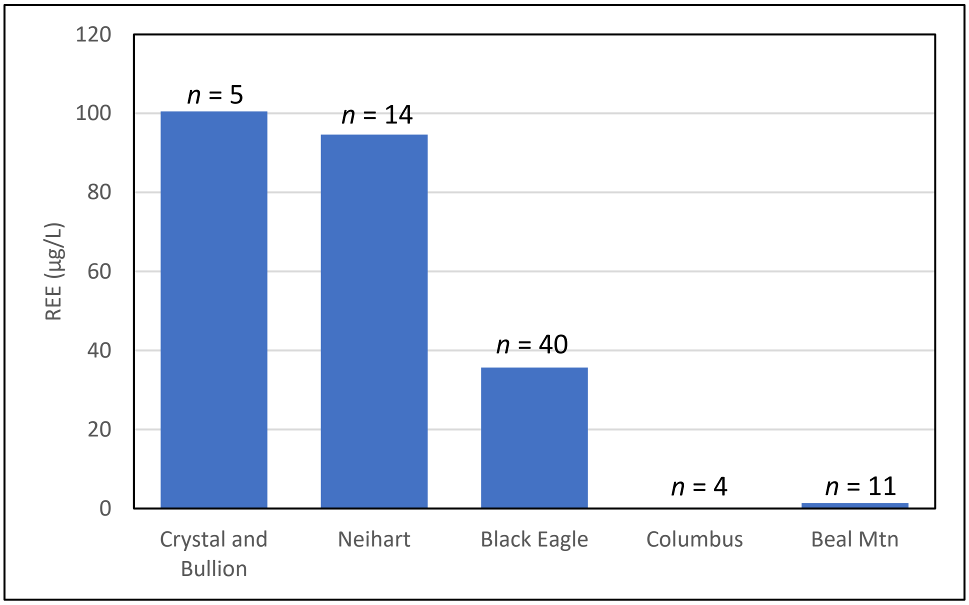

Figure 7. Average total REE concentrations per aqueous sample site below 499 µg/L.

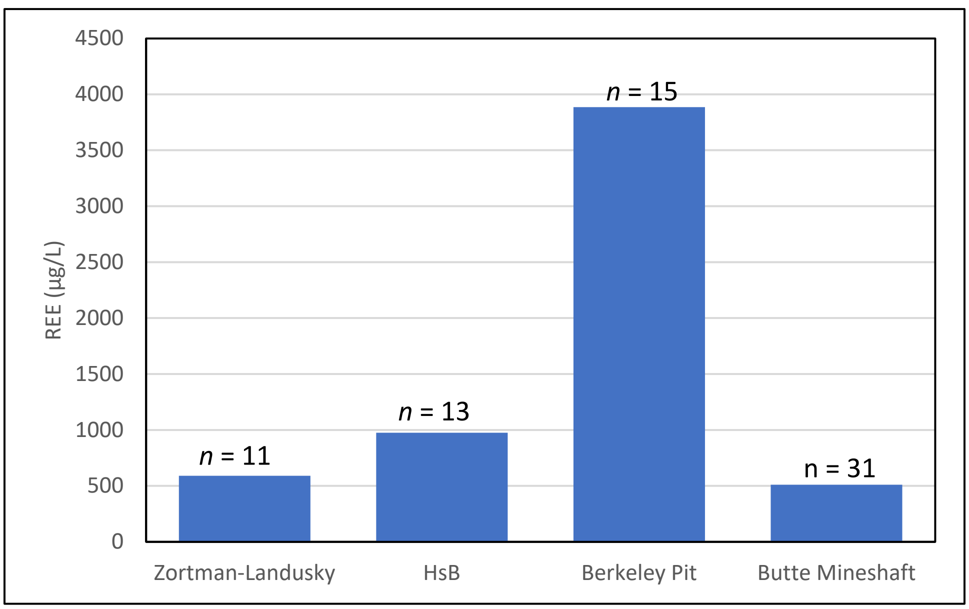

Figure 8. Average total REE concentrations per aqueous sample site above 499 µg/L.

REE concentrations were higher in surface-water and groundwater sites where pH values are less than or equal to 4.0. Sludge and solid samples from sites treating acid mine water with lime had the highest REE concentrations. Sites such as the Berkeley Pit, Horseshoe Bend AMD (HsB), and Zortman–Landusky are examples of low pH waters that are treated with lime in existing water treatment plants. The sludge generated in the treatment process produces a concentrated REE byproduct. These sites have the best potential for secondary REE recovery while reducing treatment costs and the volume of sludge stored in onsite repositories.

Future Work

Reconnaissance sampling will continue during year 2 at the 10 remaining sites, while additional samples will be collected from selected sites sampled during year 1 that showed elevated TREE concentrations. New data will be combined with year 1 results and will be used to identify sites with elevated REE concentrations (solids > 412 mg/kg, aqueous > 499 µg/L) for further, more detailed sampling. Additional areas and sample locations will be added to the sample list as they become known/identified.

Produced Publications

Quarles, J.T., Vitale, M.J., and Calhoun, M.W., Identification of rare earth element occurrences in mine waste throughout MT, 15th International Mine Waste Conference 2024 Proceedings.

Vitale, M.J., Quarles, J.T., Duaime, T.E., Roitz, J., and Calhoun, M.W., 2024, Preliminary data release of mine waste assays from abandoned and inactive mines across Montana: Montana Bureau of Mines and Geology Analytical Dataset 12, https://doi.org/10.59691/MPEH6372

Duaime, T.E., Quarles, J.T., and Vitale, M.J., Identification and characterization of rare earth elements in large-scale mine wastes—Task 4 data summary report: Year 1 (2022-2023): Montana Bureau of Mines and Geology Open-File Report 769, https://doi.org/ 10.59691/SJXG9822

References

Balaram, V., 2019, Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geoscience Frontiers, v. 10, no. 4, p. 1285–1303, https://doi.org/10.1016/j.gsf.2018.12.005

Seredin, V. and Dai, S., 2011, Coal deposits as potential alternative sources for lanthanides and yttrium: International Journal of Coal Geology, v. 94, https://doi.org/10.1016/j.coal.2011.11.001

MT-REEP Task 5—Assessment of Critical Mineral Commodities in Montana's Abandoned Mine Lands

Executive Summary January 2025

Task Lead: Adrian Van Rythoven

Introduction

This task aims to assess the rare earth element (REE) potential in mine waste (and remaining unmined deposits) from abandoned or inactive mines or prospects in Montana. These are typically small mines that produced metallic minerals.

During the 1900s, Montana was a significant producer and refiner of precious and base metals, with hundreds of mines, mostly in the western part of the State. Currently, limited precious and base metal mining and milling occur at a handful of sites.

Objectives

The Task's goal is the assessment of mining-related entities in Montana for critical minerals (primarily REEs, but also germanium, gallium, antimony, etc.). Most of the targeted entities are former small metallic mineral mines that range from abandoned to completely reclaimed. These assessments incorporate reconnaissance mapping, sampling, and field measurements (structural, geophysical, and geochemical). Sampled materials at these entities include tailings, waste rock, slag, leach residues, and rock outcrops. These samples are then processed into representative splits for assay, thin section, and archival samples. Thin sections are used to collect mineralogical and textural information about the mineral deposit that complements the chemical assay data.

These collected data provide an understanding of the nature of mineralization in the deposit. This allows for a preliminary, but comprehensive, assessment of the feasibility of critical mineral extraction at each entity. Based on this reconnaissance work, the assessed entities can be ranked not only in terms of contained critical minerals, but also by the feasibility of their production.

Activities July 2022 to October 2024

A total of 212 samples were collected across about two dozen different entities, mostly in southwestern Montana (fig. 1).

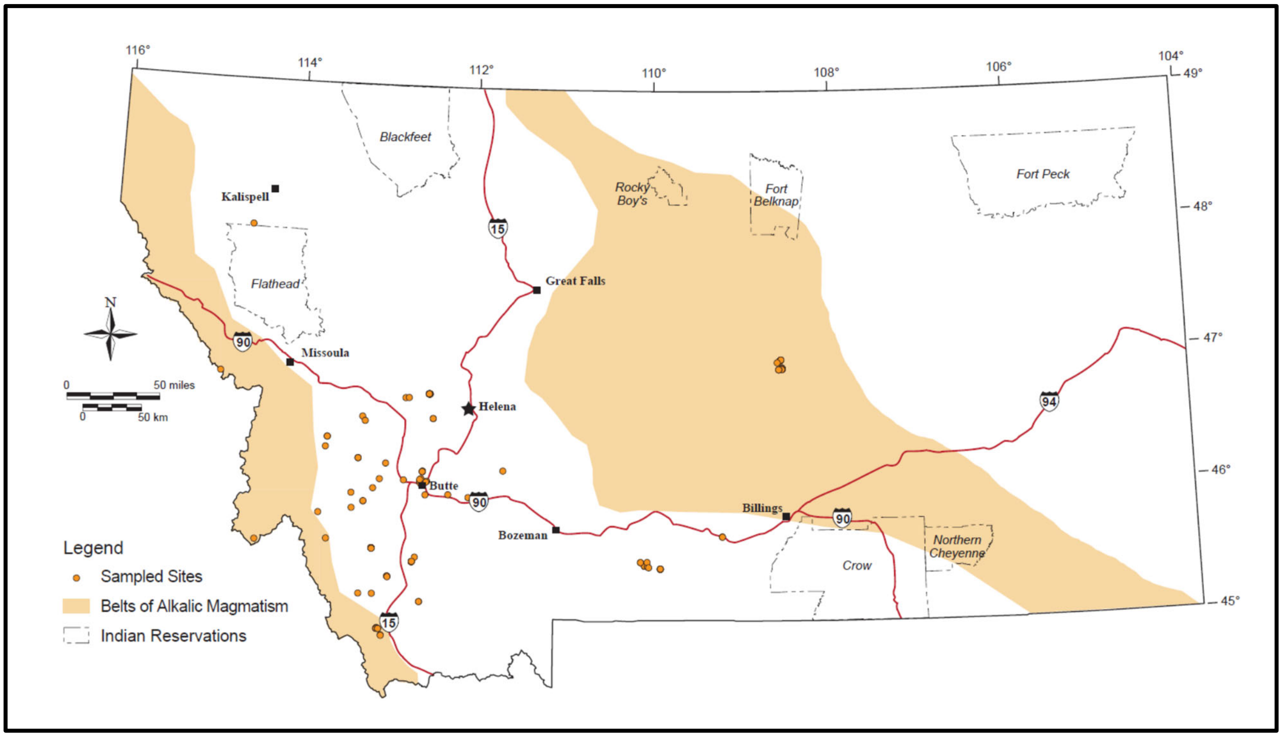

Figure 9. Geographic distribution of sampled sites. Also shown are belts of alkalic magmatism.

The samples were assayed for 66 different analytes across five different methods by ALS Global using analytical package CCP-PKG01. Additionally, Au, Pd, and Pt were analyzed by fire assay using the PGM-ICP27 method at the same lab.

To characterize the microscopic textures of the samples, representative rock sample splits were mounted on a glass slide as a polished thin section for optical microscopy analysis in reflected and transmitted light. Mineralogical characterization was completed by automated mineralogical analysis using a scanning electron microscope. These data allow for detailed assessment of the rock's economic potential with an aim to extract the mineral resource(s).

Funded M.S. student Everett LaBudda is focused on the historic and undeveloped Boulder Porphyry Deposit north of Butte. This work is in collaboration with a private mineral exploration company that has provided drill core for assay and hyperspectral mineralogical analysis. This study's goal is to develop exploration vectoring tools for porphyry-type deposits that can host significant critical minerals such as Te, Sn, W, and Pd.

Notable Results

Rare Earth Elements: The highest REE contents (>15 wt.% REE+Y, including up to 1 wt.% Nd) were found in carbonatite and related types of deposits. These carbonatite samples are typically enriched in the light REEs (La through Gd), and slightly enriched in the heavy REEs (Y and Tb through Lu). There are two regions (belts) of alkalic magmatism in the State where these carbonatite-related deposits are located. These two belts are shown in the above map (fig. 1): (1) The Montana–Idaho Alkalic Belt (e.g., Snowbird, Tendoys, Sheep Creek), and (2) the Central Montana Alkalic Belt (e.g., Petroleum County). Thus far, three entities have been visited in (1) and one entity has been visited in (2). Both belts have many other reported occurrences of REE mineralization yet to be visited in this Task. Most typical metal-sulfide deposits sampled (and their wastes) do not have significant REE grades, although a few samples of slag from Sibanye–Stillwater's Columbus refinery do concentrate some REEs. Additionally, tailings from commercial sapphire production at Rock Creek (Granite County) also host small amounts of high-grade heavy REEs. Figure 2 shows a comparison of the most promising REE grades on a chondrite-normalized plot (also shown is a typical Montana metal-sulfide mine waste sample).

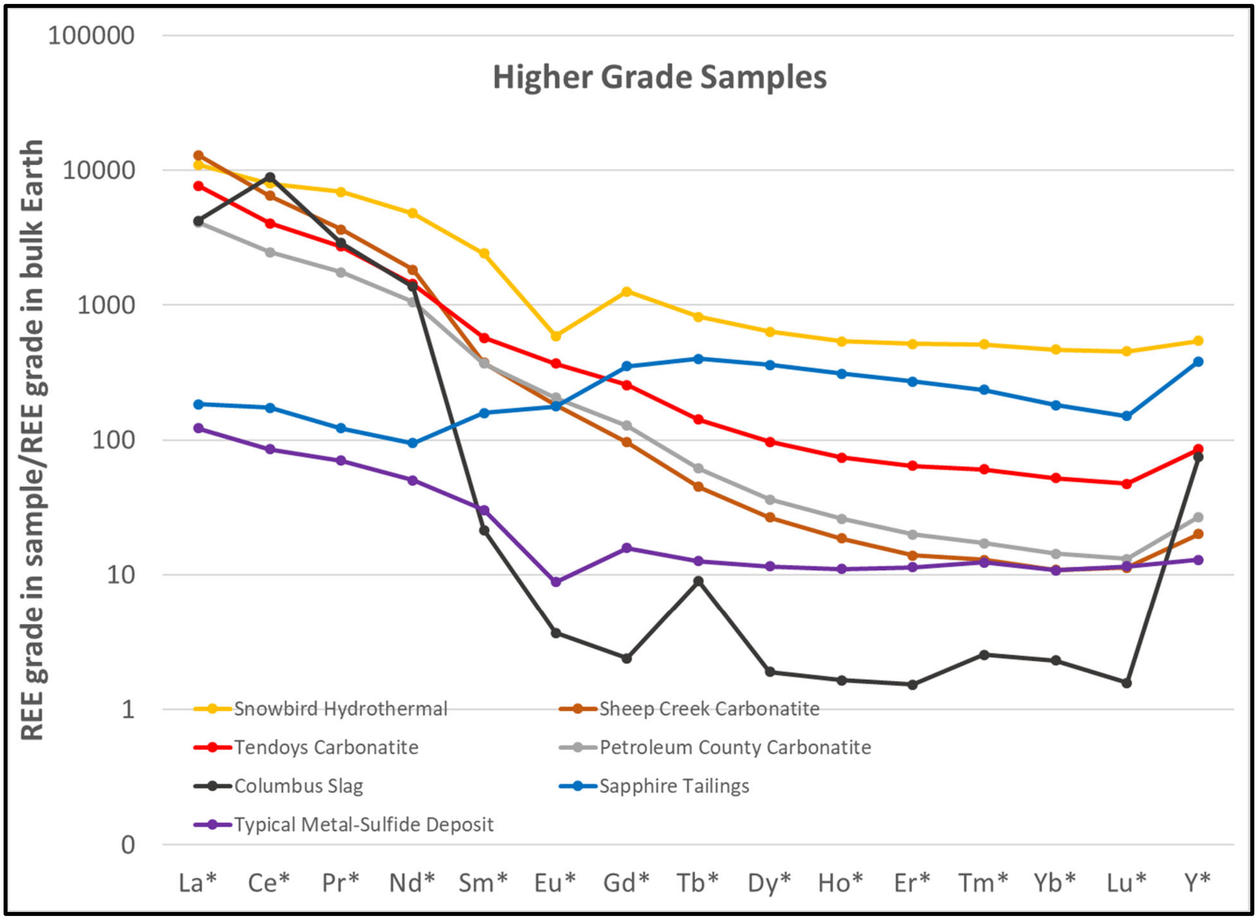

Figure 10. A chondrite-normalized plot of normalized REE concentrations for the highest-grade samples in this study. Chondrite-normalized plots essentially show an "enrichment factor" of concentration for each individual REE on one diagram, allowing for easier comparison.

Other Critical Minerals: Most of the sampled mines in Montana are in metal-sulfide deposits, and despite low REE grades, these do have potential for Pt, Pd, Rh, Ga, Ge, Sb, Te, Bi, Co, Ni, Zn, Sn, Bi, and/or In. Furthermore, a visit to the historic graphite mines in the Dillon area (Beaverhead County) showed high potential for re-mining in the area. Finally, Montana hosts the most significant deposits of W and Cr in the country. A ferrochromium refiner in the eastern U.S. is considering restarting a 1960s-era mine in Montana (the Mountainview Mine) to attain domestic feedstock. Samples from the Mountainview Mine show potential for Ni, Co, Pt, and Pd in addition to Cr. The aforementioned carbonatite REE deposits also have significant Zr, Hf, Nb, and Ta. The Columbus slags host high-grade Zr, Hf, Mg, Ti, Cr, and Nb in addition to some REEs.

Other Commodities: Most of these metal-sulfide deposits have significant grades of Au, Ag, Cu, Pb, Mo, and other base metals. Such metals are typically the major host for value in these deposits, with the critical minerals only being sustainable in open-market production as a byproduct.

Produced Publications

Van Rythoven, A., Scarberry, K., and Risedorf, S., 2024, Preliminary data release of whole-rock assays from rare earth and niobium deposits in Ravalli County, Montana: Montana Bureau of Mines and Geology Analytical Dataset 11, https://doi.org/10.59691/VLKD7955

Van Rythoven, A., Scarberry, K., and Eastman, K., 2024, Preliminary data release of whole-rock assays from active and inactive minerals and metal mines in southwest Montana: Montana Bureau of Mines and Geology Analytical Dataset 10, https://doi.org/10.59691/IAFN6749

Van Rythoven, A., Scarberry, K., and Eastman, K., 2023, Preliminary data release of whole-rock assays from active and inactive mines in southwest Montana: Montana Bureau of Mines and Geology Analytical Dataset 7, https://doi.org/10.59691/PESC1524

Planned Future Work

The variety of mine deposit type samples and their variance in critical mineral grades and textures necessitates further sampling. An optimistic goal is another 250 to 400 samples.

Everett LaBudda's M.S. project should provide completed geochemical tools to assist in evaluation of certain critical mineral deposits by the end of summer 2025.

The REE carbonatite deposits discovered in the Tendoy Mountains and Petroleum County both require detailed study beyond reconnaissance sampling to assess their nature and extent. Recruitment of an M.S. student to study these deposits is planned for next year.

Renewed interest in the Cr deposits of the Stillwater Complex (including the Mountainview Mine) by industry warrants further collaboration. This case of critical mineral development has one of the shortest foreseeable timelines to production of any proposed venture in the U.S. Further assessment with industry partners is planned for future years.

MT-REEP Task 7—Rare Earth Element Concentrations in Coal and Associated Sediments in Central and Eastern Montana

Executive Summary January 2025

Task Lead: Ryan Davison

Introduction

Task 7 aims to determine the potential of rare earth elements (REE) in Montana coal. Coal underlies over 35% of Montana and generally increases in maturity east to west across the State (lignite–subbituminous–bituminous; fig 1). Major deposits occur in the late Jurassic (163–145 Ma), Cretaceous (145–66 Ma), and Tertiary (66–2.6 Ma). Historically, coal in Montana has been mined for energy purposes, primarily from the Tertiary deposits (Fort Union Formation), because these coalbeds are thick and accessible for strip mining. Coals from all three time periods occur in outcrops that generally decrease in number east to west and south to north. Locating outcrops of coal in northern Montana is especially difficult due to the glacial sedimentary cover left by the Laurentide Ice Sheet advances during the Pleistocene Epoch (2,600,000 to ~12,000 years ago).

Objectives

The primary objectives are to: sample coalbeds and associated sediments in outcrop across Montana, collaborate with active coal mines and sample coalbeds, identify and characterize areas with elevated REE concentrations, and provide recommendations for areas conducive to mining coal for REE.

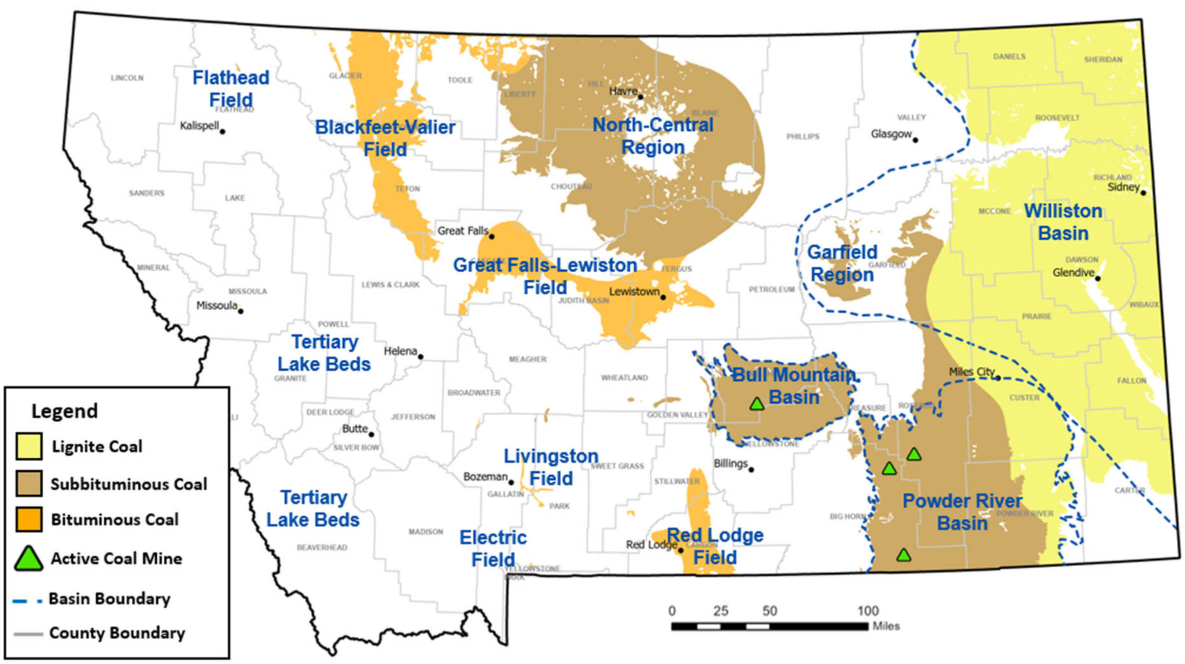

Figure 1. Map of the major Montana coal regions (modified from Cole and others, 1982).

Activities 7/2022–10/2024:

- *A complete review of existing Montana coal literature:* Much is known about the active and inactive coal mines in Montana, but they represent very small portions of the State's total coal potential. Locating literature covering the lower quality, "uneconomic," or forgotten coal seams required significant research. No coal literature specifically focused on REE in coal.
- *Digitizing historic coal maps:* Historically, most coal mapping is focused on the east side of the State due to the thick deposits found there. However, there were many maps going back to the late 1800s that were invaluable for identifying coals to sample across the entire State. All of these maps were digitized and added to the coal project.
- *A review of coal databases to identify available coal/sediment assay results:* Previous to this study, only a small percentage of coals in Montana had been assayed for REE. The MBMG has conducted previous coal studies in the eastern part of Montana for the purpose of determining coal quality. The coal database produced from this work identified hundreds of potential sample locations, but gave little indication of REE potential. The USGS COALQUAL database (Palmer and others, 2015) was less useful. Many samples were from core and represented only a small portion of the total coalbed. REE are usually concentrated in specific portions of a coalbed (upper or lower in most cases).
- *Collaboration with Montana coal mines:* This was the most logical place to start the study, as coal mines usually have great access to thick, high-quality coalbeds. Three mines were sampled in the Powder River Basin: Absaloka, Rosebud, and Spring Creek, and one in Bull Mountain Basin: Signal Peak. The results have unfortunately been disappointing. Overall, large, clean coalbeds do not contain elevated concentrations of REE.
- *Coal sampling:* A total of 952 coal samples from 285 individual sites have been collected as of 10/2024 (fig. 2). A majority of the samples have been collected on Federal land. Samples were primarily collected in outcrop, except when collected at the mine locations. Moving west across the State, coal exposures become more elusive and identifying them will be a focus in the future.
    - **Year 1** was a reconnaissance year, since there was no work to build upon for assessing Montana coal for REE. Therefore, samples during year 1 were collected wherever there was access to coal, without a focus on detailed geologic description. This allowed for quick and easy coal sampling and subsequent identification of coals with high concentrations of REE for future, in-depth work. A total of 262 samples from 94 sites were collected in eastern Montana.
    - **Year 2** investigated coals with elevated concentrations of REE identified in year 1, and expanded sampling into central and western Montana. Coals with concentrations of REE well above 300 ppm were discovered in the Powder River Basin and Great Falls area. A total of 480 samples from 133 sites were collected in year 2.

- **Year 3** work continues to map and sample new coals. Further investigation of the Powder River Basin and Great Falls area has produced more positive results. Several characteristics have been identified in REE-rich coals that can be used to identify additional beds. A total of 210 samples from 58 sites in year 3 have been collected as of 10/2024.

Montana Coal Sample Sites

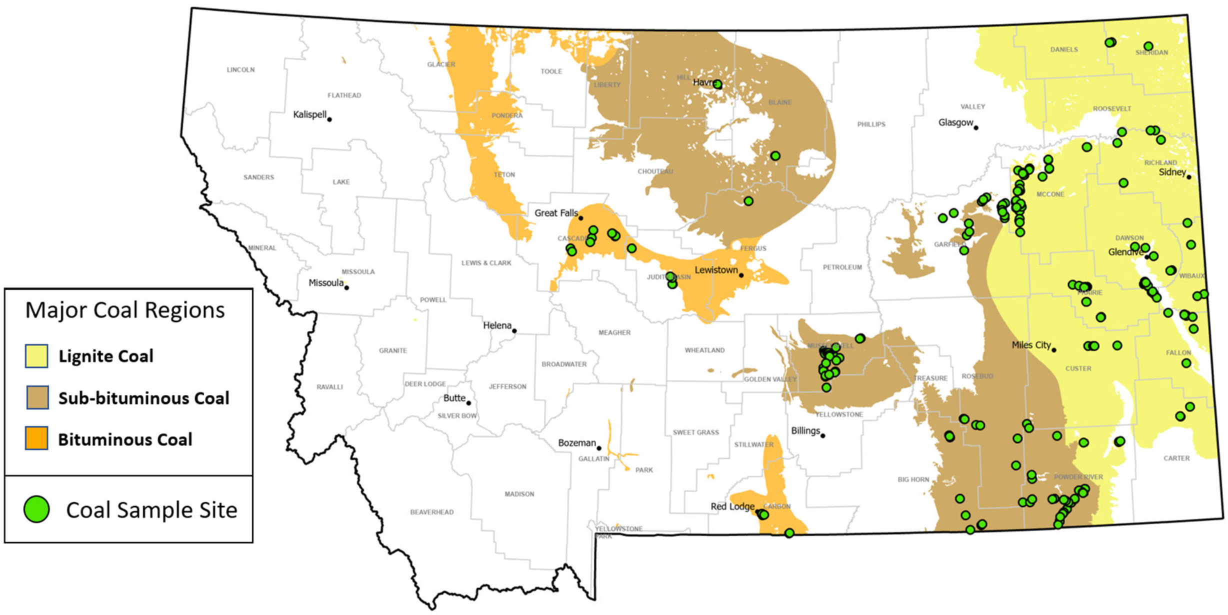

Figure 2. Map of coal sample locations to date.

Assay Results

All samples were analyzed on a dry rock/whole-coal basis. Analyses were performed using inductively coupled plasma mass spectrometry (ICP-MS) by ALS in Reno, NV. Samples were tested for the following elements: Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Ge, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn, Zr, Dy, Er, Eu, Gd, Ho, Lu, Nd, Pr, Sm, Tb, Tm, and Yb.

A complete list of year 1 results has been released as an analytical dataset (Davison, 2024). Year 2 assay results will be released in early 2025. The average REE for all coal samples is 93 ppm. This number is higher than the U.S. coal average of 62 ppm, but far below the DOE-suggested 300 ppm economic threshold (DOE, 2017). Taking into consideration the differing geologic environments, the different coal types, and the overall differences in the coal seams sampled, this average number is not surprising. Overall, most coalbeds will have average REE concentrations. However, there are beds that are enriched with REE for reasons that are poorly understood.

The Sawyer coalbed in the Powder River Basin has REE concentrations ranging from 300 to 852 ppm (whole-coal basis) and a yet-unidentified coalbed near Great Falls has REE concentrations ranging from 200 to 667 ppm. How and why these coals have up to 10 times the average REE concentrations is something that is a focus in this study. The Powder River Basin is of particular interest due to the large amounts of Federal land, proximity to current coal production, and relatively close proximity to Wyoming REE coal projects.

ICP-MS results indicate that none of the active Montana coal mines have REE concentrations near the DOE economic threshold of 300 ppm. The coal samples collected at the mines averaged 71 ppm REE, with a minimum of 17 ppm, and a maximum of 162 ppm.

Conclusions and Future Work

The 285 sites sampled and described in this study have revealed the following about the occurrence of REE in Montana coal:

- REE enrichment often occurs in the upper or lower half of a coalbed.
- In many cases, if a coal is high in sulfur, it is high in REE.
- Clean coals (not a lot of sediment) are often low in REE.
- A sandstone usually occurs above the coals with the highest REE enrichment.
- Coals in the Tongue River Member of the Fort Union Formation have the highest REE concentrations.
- Coal leaches REE more readily than expected when exposed to weathering.

Future Work and Goals:

- Identify coals with REE concentrations >300 ppm through continued sampling. There are still many coals to sample across the State; however, 2 years of work has helped narrow the focus.
- Continue to identify common characteristics between elevated-REE beds.
- Create detailed stratigraphic descriptions of REE-enriched coalbeds.
- Theorize methods of REE enrichment in coal.
- Continue to refine sampling technique.
- Use data to work on a prediction model, similar to basin modeling that petroleum geologists use to predict oil and gas reservoirs.

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