PART I

# CRITICAL MINERALS

## BELOW NORTH DAKOTA'S OLDEST LANDSCAPES

BY LEVI D. MOXNESS

### CRITICAL MINERALS: MADE IN THE USA?

The search continues for new and alternative sources of critical minerals within the United States, as the federal push to onshore U.S. manufacturing has prompted an initiative to secure reliable sources of the raw materials needed to supply it. Mineral commodities deemed "critical" by the U.S. Department of the Interior (USGS, 2022) are those considered essential to the economic or national security of the United States which also have vulnerable supply chains due to U.S. reliance on imports from foreign producers. Any disruption to the international trade of these minerals would have significant domestic consequences to the manufacturing of essential products. This strategic vulnerability is expected to be further magnified over the coming decades as demand for many of these commodities is likely to grow dramatically alongside an increasingly electrified energy and transportation infrastructure. See previous GeoNews articles for a more thorough discussion of critical minerals and their importance to modern military, technology, and energy applications (Moxness, 2021). Considering their outsized role in vital American industries, it is no surprise there has been bipartisan federal support for investing in domestic supply chains of critical minerals.

The updated 2022 list of critical minerals is diverse: aluminum, antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite, hafnium, indium, iridium, lithium, magnesium, manganese, nickel, niobium, palladium, platinum, rhodium, rubidium, ruthenium, tantalum, tellurium, tin, titanium, tungsten, vanadium, zinc, zirconium, and the sixteen rare earth elements (REE). The rare earths, often included as a group because they are chemically similar and commonly occur together, are often the first example used when discussing critical minerals. Each plays an important role in modern industries (Table 1), but the U.S. produces only small

**TABLE 1.**
Select elements, which are produced or considered highly promising to one day be produced from world coal (Dai and Finkelman, 2018), and their respective uses (USGS, 2022). Other elements considered highly promising include Ag, Al, Au, Pd, Pt, Re, Se, and Si, which were outside the scope of the NDGS study.

**Promising Elements In Coal And Their Uses**

| | |
|---|---|
| **Rare Earth Elements** | |
| **Cerium** | Catalytic converters, ceramics, glass, metallurgy, and polishing compounds |
| **Dysprosium** | Permanent magnets, data storage devices, and lasers |
| **Erbium** | Fiber optics, optical amplifiers, lasers, and glass colorants |
| **Europium** | Phosphors and nuclear control rods |
| **Gadolinium** | Medical imaging, permanent magnets, and steelmaking |
| **Holmium** | Permanent magnets, nuclear control rods, and lasers |
| **Lanthanum** | Catalysts, ceramics, glass, polishing compounds, metallurgy, and batteries |
| **Lutetium** | Scintillators for medical imaging, electronics, and some cancer therapies |
| **Neodymium** | Permanent magnets, rubber catalysts, and in medical and industrial lasers |
| **Praseodymium** | Permanent magnets, batteries, aerospace alloys, ceramics, and colorants |
| **Samarium** | Permanent magnets, as an absorber in nuclear reactors, and in cancer treatments |
| **Scandium** | Alloys, ceramics, and fuel cells |
| **Terbium** | Permanent magnets, fiber optics, lasers, and solid-state devices |
| **Thulium** | Metal alloys and in lasers |
| **Ytterbium** | Catalysts, scintillometers, lasers, and metallurgy |
| **Yttrium** | Ceramics, catalysts, lasers, metallurgy, and phosphors |
| **Other Highly Promising Critical Minerals** | |
| **Gallium** | Integrated circuits and optical devices like LEDs |
| **Germanium** | Fiber optics and night vision applications |
| **Magnesium** | Used as an alloy and for reducing metals |
| **Niobium** | Used mostly in steel and superalloys |
| **Vanadium** | Alloying agent for iron and steel |
| **Zirconium** | High-temperature ceramics and corrosion-resistant alloys |
| **Highly Promising Non-Critical Minerals** | |
| **Molybdenum** | Steel and corrosiuon-resistant alloys, catalysts, lubricants, pigments, and fertilizer |
| **Uranium** | Nuclear fuel, isotopes used for medical, industrial, and defense purposes |

quantities, and China has used its near monopoly as leverage in international trade negotiations.

A large number of these 50 critical elements and minerals are produced from various igneous (hard rock) ores across the globe. Many comparable deposits occur in the United States but remain undeveloped, as the U.S. has outsourced production to countries with lower mining costs. The financing, resource characterization, permitting, and infrastructure buildout of a new U.S. mine can take a decade or more, so it can be difficult for developers to forecast the commodity prices and regulatory environment that will end up controlling the economics of a given deposit. This is one reason there has been considerable national interest in the potential to produce critical minerals from a resource which is already mined across the country: coal.

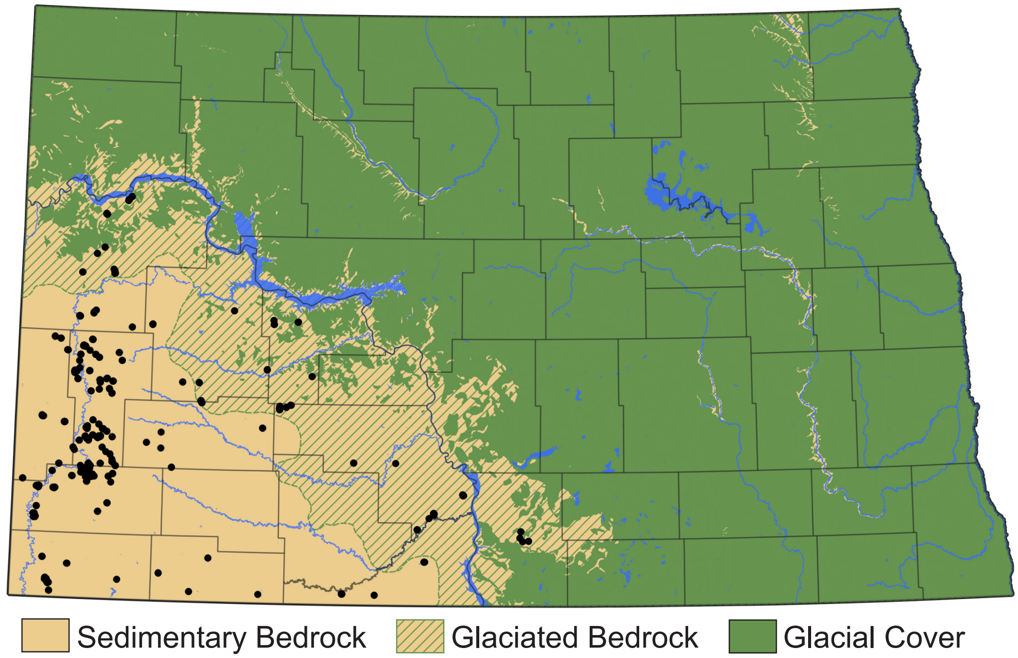


**FIGURE 1.**
NDGS samples (black dots) relative to the generalized erosional landscapes of North Dakota. Most of the state's bedrock surfaces were eroded and covered by glaciers as recently as the late Pleistocene. Other areas just southwest of the Missouri River were glaciated earlier in the Pleistocene, but were left largely exposed. The oldest landscapes in the state lie beyond the limits of glaciation, where some surfaces may have remained relatively stable since before the Ice Age.

## WHY COAL?

A nationwide review of every potential traditional (non-fuel) critical mineral resource is underway via the United States Geological Survey's Earth MRI program. North Dakota's sedimentary bedrock cover means the state has few of these traditional critical mineral resources, especially after the removal of potash and uranium from the original critical minerals list (USGS, 2018). But the United States Department of Energy (DOE) has pushed for research into utilizing coal as a non-traditional ore, which North Dakota has in abundance. Twenty-five billion tons is already considered economically recoverable in the state (Murphy, 2001), but do North Dakota lignites offer the same promise as higher-rank Appalachian coals or those from Rocky Mountain basins? At UND, research into the most cost-effective extraction methods has shown that a large portion of the rare earth elements in low rank North Dakota lignites can be easily mobilized (Laudal and others, 2018), meaning that if the U.S. plans to produce critical minerals from coal, ND lignite is a promising candidate. The DOE continues to make serious investments in this sector nationwide, announcing another $32 million in October 2022 to fund "front-end engineering design studies to produce rare earth elements and other critical minerals and materials from domestic coal-based resources." Ultimately, coal's competitiveness with traditional ores hinges on the identification of sufficiently enriched feedstocks, but with less than 200 of 7600 entries in the national coal geochemical database representing North Dakota lignites (Palmer and others, 2015), extensive characterization work was needed to assess the state's potential.

## NDGS INVESTIGATIONS

The North Dakota Geological Survey (NDGS) began its study into the rare earth contents of ND lignites in 2015 (Kruger, 2015), releasing its first report of randomized sampling across southwestern North Dakota in Kruger and others (2017). Now the NDGS has collected over 2,000 samples, from over 300 stratigraphic sections (fig. 1) and will have 1,650 samples analyzed for rare earths by the end of 2022. Rare earth elements have been the focus, but 28 other additional elements were added to the investigation with the release of the federal critical minerals list in 2018. Identifying if any of these other valuable minerals are found alongside rare earths in ND coal is especially relevant, since any future development from coal resources may look to co-produce multiple mineral commodities if they occur together and can be extracted in valuable quantities using similar processing streams. Promising concentrations of other elements (e.g., gallium and germanium) are known to occur in coal (Dai and Finkelman, 2018) and could in turn lower the overall rare earth concentrations needed for a deposit to be considered economic.

The first NDGS report in 2017 established that North Dakota lignite can indeed contain elevated rare earth concentrations, with 22 of the first 352 samples meeting the 300 parts per million (ppm) threshold considered promising by the DOE. Subsequent reports have focused on establishing the extent of REE-enriched zones and identifying the geologic context in which enrichment occurs, with the ultimate goal of developing an exploration model (Kruger, 2017; Murphy, 2019). How often do lignites across the state contain high concentrations of rare earths? What is the highest degree of enrichment possible in ND coal? What are the lateral and vertical extents of enrichment within individual beds? Which other mineral concentrations are enriched in these same coals? To thoroughly answer these questions via a sampling-based resource characterization would surely require tens of thousands of analyses or more, but more targeted exploration can take place if a more fundamental question can be answered: How did the rare earths get there in the first place?

Seredin and Dai (2012) proposed several possible enrichment methods. The rare earths may have entered the ancient peat bogs and swamps as the coal was being deposited via pulses of enriched surface waters or volcanic ash. Enrichment can also occur after the coal was buried, from below via ascending hydrothermal fluids, or from above via infiltration through the overlying sediments. The latter scenario has been used to explain the accumulations of other elements (uranium) found in North Dakota's coals (Denson and Gill, 1965). As the volcanic sediments of the White River Group weathered and eroded, mineral matter was dissolved and transported downward by groundwater until it was bound to the organic matter in lignites. The NDGS explored this same model for rare earths, visiting former uranium mines and analyzing radioactive lignites, but found that rare earth enrichment must occur somewhat independently. Lignite samples which contained thousands of times more uranium than average contained relatively normal rare earth concentrations and conversely, the state's highest rare earth concentrations seem to occur in lignites which are not particularly enriched in uranium (Kruger and others, 2022). This may suggest the White River Group volcanics are not the original source of the rare earths. Researchers in other states (Kentucky, Wyoming) with elevated rare earth concentrations in coal have attributed their enrichment to volcanic ashes within or directly adjacent to the coal. The NDGS recently investigated several of North Dakota's known volcanic deposits within coal-bearing strata (Moxness and others, 2022; Kruger and others, 2022). The "blue bed" ash and bentonite in McKenzie County (fig. 2), the Linton ash in Emmons County, the Breien ash in Morton County, the Marmarth ash in Bowman County, and the Hanson tonstein in Slope County do not appear to contain high concentrations of the rare earth elements, or to have leached them into adjacent lignites.

One pattern that was noticed as the study progressed was the tendency for the highest lignite in a given outcrop to contain the highest rare earth concentrations. This was especially apparent where a level upper prairie was present at the top of the outcrop, such as Tracy Mountain in Billings County (Moxness and others, 2021) and Mud Buttes in Bowman County (Moxness and others 2022). Here multiple thin lignites and carbonaceous mudstones are enriched above 300 ppm, with some samples exceeding 1000 ppm. Almost all of the enrichment occurs in the upper 70 feet, and the samples collected from 70 to 300 feet below the top of the buttes contained concentrations more normal for ND lignite (fig. 3). Were these coals enriched when the White River Group volcanics eroded away above them? These surfaces were likely hundreds of feet below the former contact with the White River Group, but even if not, where was the uranium? None of the beds emitted levels of radiation above background and every sample analyzed for uranium was within normal (non-uraniferous) ranges for ND coal.

Perhaps these intervals capture a period of Paleocene time where rare earths were entering coal swamps, and they just happened to now be exposed at the tops of buttes? Since these upland surfaces are erosional, they occur at many different stratigraphic positions across millions of years of deposition. The topographic (vs. stratigraphic) controls on enrichment are most easily seen at smaller scales. At an outcrop four miles south of Mud Buttes, the upland surface occurs 150 feet lower stratigraphically, but with similarly high enrichment (661 ppm) in the uppermost coal.

Another noteworthy characteristic of these buttes is they are not protected by thick impermeable caprocks like many of North Dakota's iconic buttes (Sentinel Butte, Square Butte, Bullion Butte, the Killdeer Mountains, etc.). The headward erosion carving the Little Missouri badlands just hasn't gotten to them yet. Thus, the tops may preserve erosional remnants of the major surface that spanned from one side of the Little Missouri badlands to the other prior to the onset of downcutting spurred by ice-age base level changes. There is little geochronological data to help determine the age of these now-uplands beyond geomorphic inferences, but it is reasonable to conclude these surfaces could be at least early

**FIGURE 2.**
The Sentinel Butte volcanic ash in McKenzie County north of Theodore Roosevelt National Park. A white tuff weathers to "blue bed(s)" of bentonite above and below. Like other volcanic sediments investigated across the surface of ND, neither it nor the adjacent coals appear enriched in critical minerals.

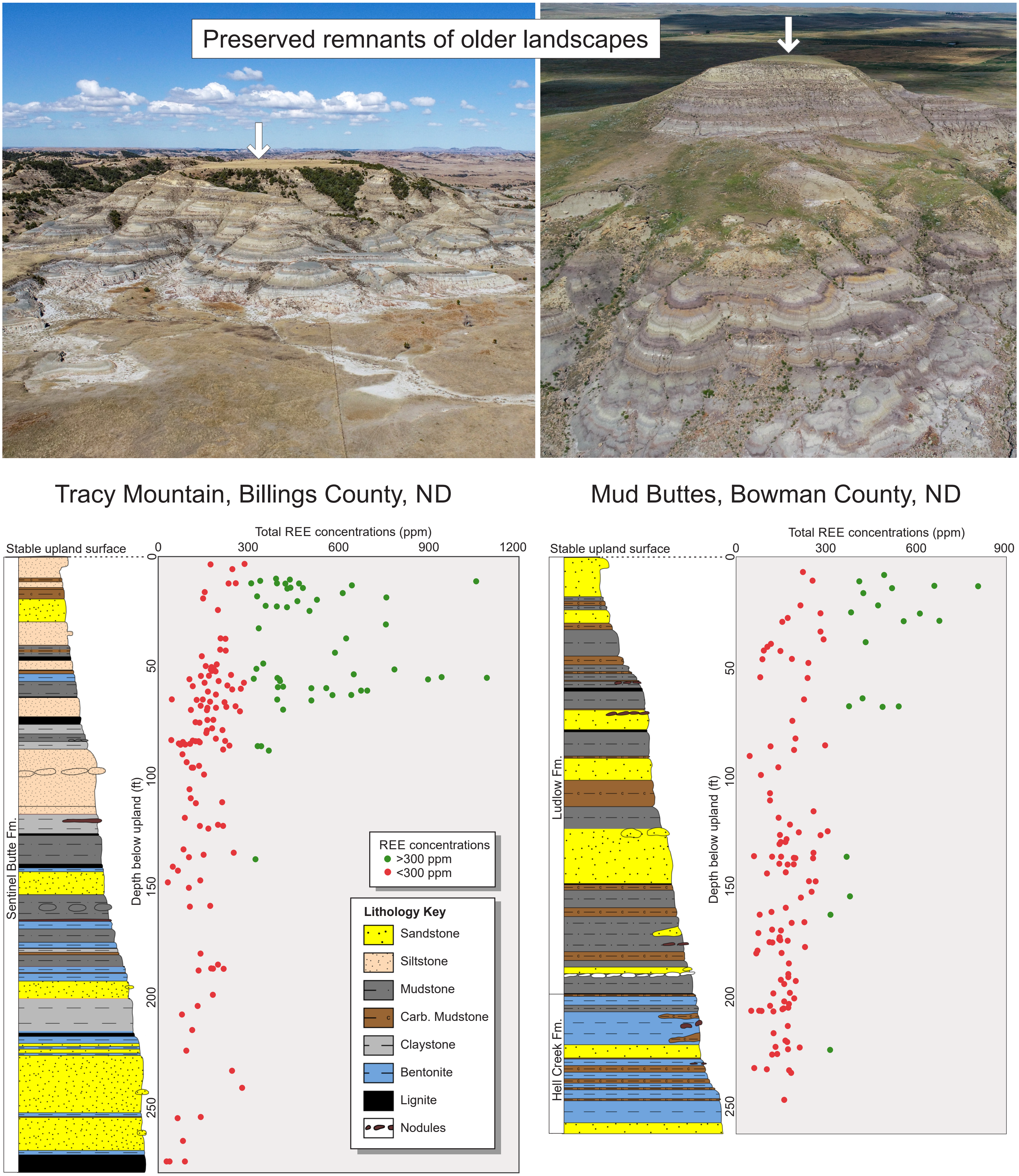


**FIGURE 3.**
Tracy Mountain (left) and Mud Buttes (right). Both buttes contain multiple REE-enriched lignites and carbonaceous mudstones in upper portions of their stratigraphic sections, just below level upland surfaces. These surfaces are underlain mostly by weakly cemented silts and sands, which may have facilitated the long-term infiltration of meteoric waters to leach and transport REE downward into the organic-rich beds.

Pleistocene if not Pliocene in age, exposed and chemically weathering since before the Ice Age. With flat tops comprised of relatively permeable silty sediments, infiltration of weakly acidic meteoric waters may have had ample time to leach rare earths from large volumes of sediment containing normal rare earth values (around 180 ppm) and concentrate them five-fold or more in the lignites below.

At one foot thick or thinner (fig. 4), none of the lignites found in this setting at Tracy Mountain or Mud Buttes would be candidates for mining, but how much enrichment would have occurred if the coal had been several feet thick? Or even closer to the surface? Whether or not the duration and intensity of this weathering is enough to enrich sufficient volumes of the underlying lignites to a grade considered economic remains to be seen. Tracy Mountain and Mud Buttes were investigated because of easy access but are only two isolated examples of what may be a widespread geologic setting. Much of the upper prairie flanking the Little Badlands in southwestern North Dakota may be the same long-lived, weathered, and leached landscape. We know this area also contains lignites in the near subsurface, so it is likely that the maximum possible enrichment under a "recent weathering" model remains undiscovered. Without the outcrops offered by badlands erosion it would require the integration of drilling into future exploration programs. In the meantime, the NDGS continues to investigate another suite of samples enriched in critical minerals that cannot be explained by this model (see the next Geo News for Part II).

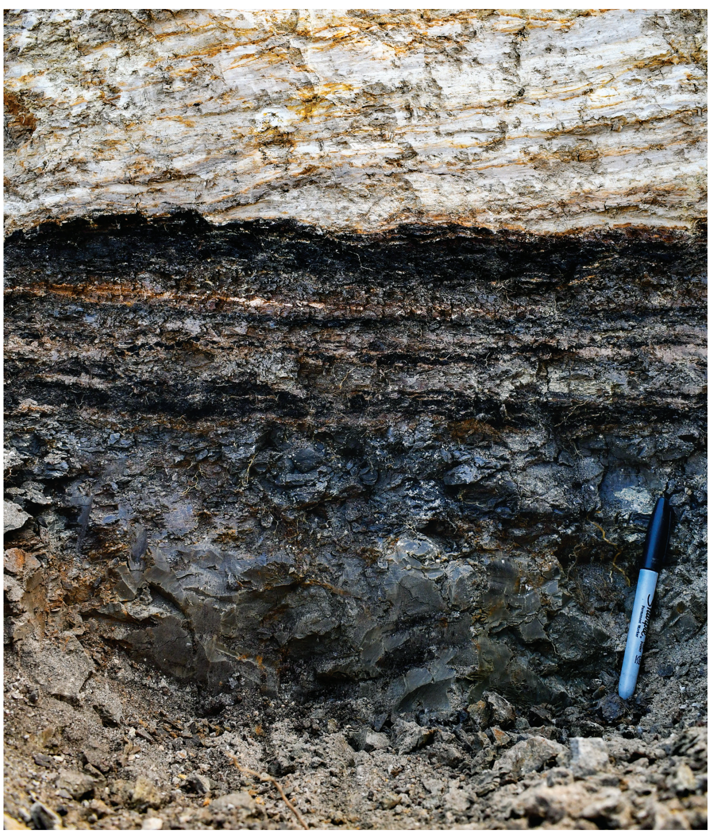

**FIGURE 4.**
A thin lignite (sample 2B from Moxness and others, 2021) beneath silty mudstone, roughly 20 feet below the top of Tracy Mountain, containing 1,054 ppm of rare earths. Marker for scale.

## REFERENCES


Dai, S., and Finkelman, R.B., 2018, Coal as a promising source of critical elements: Progress and future prospects; International Journal of Coal Geology, no. 186, p. 155–164.

Denson, N.M., and Gill, J.R., 1965, Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston Basin – a regional study: United States Geological Survey Professional Paper 463, 75 p.

Kruger, N.W., 2015, A "Rare" Opportunity: Geo News, v. 42, no. 1, p. 7-9.

Kruger, N.W., 2017, Rare earths in coal: Geo News, v. 44, no. 1, p. 10-12.

Kruger, N.W., Moxness, L.D., and Murphy, E.C., 2017, Rare earth element concentrations in Fort Union and Hell Creek strata in western North Dakota: North Dakota Geological Survey Report of Investigation 117, 104 p.

Kruger, N.W., Moxness, L.D., and Murphy, E.C., 2022, Rare Earth and Other Critical Element Concentrations in the Sentinel Butte and Bullion Creek Formations (Paleocene), Billings, McKenzie, and Golden Valley Counties, North Dakota: North Dakota Geological Survey Report of Investigation 131, 90 p.

Laudal, D.A., Benson, S.A., Addleman, R.S., and Palo, D., 2018. Leaching behavior of rare earth elements in Fort Union lignite coals of North America: International Journal of Coal Geology, v. 191. P. 112-124.

Moxness, L.D., 2021, Critical Minerals in North Dakota: Geo News, v. 48, no. 1, p. 1-4.

Moxness L.D., Murphy, E.C., and Kruger, N.W., 2021, Rare Earth and Other Critical Element Concentrations in the Sentinel Butte Formation, Tracy Mountain, North Dakota: North Dakota Geological Survey Report of Investigation no. 128, 65 p.

Moxness L.D., Murphy, E.C., and Kruger, N.W., 2022, Critical Minerals in the Fox Hills (Cretaceous), Hell Creek (Cretaceous), and Ludlow (Paleocene) Formations in North Dakota: North Dakota Geological Survey Report of Investigation no. 130, 84 p.

Murphy, E.C., 2001, Strippable lignite deposits of North Dakota, North Dakota Geological Survey Miscellaneous Map No. 34, 1:1,000,000 scale.

Murphy, E.C., 2019, Rare Earth Study: Geo News, v. 46, no. 1, p. 1-3.

Palmer, C.A., Oman, C.L., Park, A.J., Luppens, J.A., 2015. The U.S. Geological Survey coal quality (COALQUAL) database version 3.0. In: Data Series, Reston, VA, pp. 57.

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

U.S. Geological Survey, 2018, Draft Critical Mineral List—Summary of Methodology and Background Information – U.S. Geological Survey Technical Input Document in Response to Secretarial Order No. 3359.

U.S. Geological Survey, 2022, Final List of Critical Minerals, 87 Fed. Reg. 10381 (February 24, 2022). https://www.federalregister.gov/documents/2022/02/24/2022-04027/2022-final-list-of-critical-minerals.