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ON THE COVER:
Looking northwest across Logging Camp Ranch to Tepee Buttes, Bullion Butte in the background. Photo by Ed Murphy.

CRITICAL MINERALS

BELOW NORTH DAKOTA'S ANCIENT SUBTROPICAL SOILS

BY LEVI D. MOXNESS

MINERAL SUPPLIES AS CRITICAL AS EVER

As discussed in Part I (Moxness, 2023), the pressure on the United States to secure reliable sources of critical minerals is a product of several converging factors. American imports are subject to geopolitical tensions with countries that produce the world's supply of minerals. Even if the threats to restrict exports to the U.S. are never implemented, the lack of domestic production weakens the U.S. position in trade negotiations and undermines foreign policy. Reshoring U.S. manufacturing, one of the few consistent bipartisan priorities in recent years, does little to fix the overall strategic vulnerability if the raw materials needed are still mostly sourced from adversarial foreign countries. In 2020, China announced sanctions on U.S. defense contractors Lockheed Martin and Raytheon to restrict their access to rare earth elements over tensions regarding arms sales to Taiwan, which Chinese state-affiliated media would later credit for delays in F-35 fighter jet production (Asia Times, 2022).

The latest critical mineral chess pieces involve gallium and germanium, which are used in the manufacture of semiconductors, vital components in most high-performance technology. China announced export restrictions on these two elements in July of 2023, likely as retaliation for the US CHIPS and Science Act of 2022, which limited the export of microchips and advanced technology to China. The United States imports all of its gallium and most of its germanium, and more than half of each was sourced from China last year (USGS, 2023). As for the rare earth elements, despite what is now several years of scrambling to develop more domestic production, the United States' only major commercial source remains Mountain Pass Mine in California. Minor additional production of rare earths from monazite in heavy mineral sands in the southeastern U.S. has done little to reduce the reliance on imports, which were up nearly 40% between 2021 and 2022, 74% of which overall were from China (USGS, 2023).

The fact that the U.S. needed to import more rare earths last year, despite its own production climbing, illustrates the other force driving the recent wave of critical mineral exploration - demand is outpacing supply. Even if tensions between the U.S. and China ease, some estimates forecast a global undersupply of magnetic rare earths (neodymium, praseodymium, dysprosium, terbium) of nearly 62,000 metric tons annually by 2030 and over 246,000 tons by 2040, as it will be difficult for new mines to meet an estimated 7% annual demand growth (Mining.com, 2023). In the near future, countries could limit exports to the U.S. not because of geopolitical posturing, but to prioritize short supplies for their own industries.

SEMI-RARE ELEMENTS WITH VERY RARE ORES

The United States is fortunate to have a world-class rare earth deposit at Mountain Pass mine, which hosts an ore with an average total rare earth oxide grade of 8.9% (Liu et al., 2023). Additional promising resources like Round Top (Texas), Bear Lodge (Wyoming), Elk Creek (Nebraska), and Bokan Mountain (Alaska) are at varying stages in the long road from resource assessment to realized production. Even with the identification of these new traditional hard rock deposits, the U.S. Department of Energy (DOE) has been steadily investing in characterizing the critical mineral contents of U.S. coal and developing extraction technologies for coal-hosted minerals. It has used 300 parts per million (ppm) rare earth elements as a rough threshold for potentially promising concentrations in coal. Why would the DOE propose 300 ppm as a promising concentration in coal when an American mine is actively excavating a hard rock ore containing 250 times that?

Coal has some advantages over hard rocks as a mineral ore. Not all ores of the same overall grade are created equal, since different ores contain different proportions of each element and certain rare earths are 1,000 times more valuable than others. Cerium and lanthanum are two of the "least rare" rare earths (Table 1), and market prices reflect that. Oxides of these two elements are worth less than a dollar per pound and make up over 83% of the total rare earth content of Mountain Pass carbonatite, which is effectively economic solely on its neodymium and praseodymium production. These four elements, along with samarium and europium, represent the light (by atomic weight) rare earth elements. The more valuable, "rarer", heavy rare earths make up just 0.49% of the total rare earth element content at Mountain Pass and are not even currently economically recoverable using existing processing techniques. By contrast, the average North Dakota lignite with rare earth concentrations of 300 ppm or greater can be as much as 50% heavy rare earths and scandium (a highly valuable rare earth not traditionally grouped with the light or heavy elements as it does not occur in hard rock ores), with an average of 29%.

HOW ORE TYPE INFLUENCES ECONOMICS

Rare earths and other critical mineral commodities can best be thought of as elements locked inside of minerals locked inside of rocks. To get these elements out of the ground and into a smartphone, wind turbine, electric car, or nuclear submarine requires mining, beneficiation, leaching, separation, refining, alloying, and manufacturing. Mining rock is a relatively straightforward process, although it is marginally more costly to mine veins of hard rock in the mountains than it is to mine a flat-lying lignite just below the surface on the plains, especially if that lignite is already economically mined to supply a thermal power plant. The most cost savings are to be found as the elements are extracted from the minerals. Monazite, xenotime, bastnäsite, and other REE-bearing minerals found in hard rock are expensive to break down. This can involve high temperature roasting and acid digestion after ultra-fine grinding and gravity or magnetic separation. As you leach the rare earth elements from these minerals, alongside them are radioactive contaminants uranium, thorium, and all the associated costs of handling radioactive waste. Coal may be far less enriched in rare earth elements than these traditional ores, but it is also typically less enriched in the contaminants, making it far easier to avoid indirectly concentrating uranium and thorium above strict regulatory thresholds.

Since most of the cost to produce rare earths from traditional ores involves the mechanical breakdown of rock, followed by acid leaching of the primary minerals to release the elements, it's more economic to find a setting where nature has already done most of the work. Placer deposits of heavy mineral sands can be economic where they concentrate rare earth-bearing mineral grains, but the mineral grains themselves still need to be broken down. The most economic deposit, which supplies almost all of the world's heavy rare earth supplies, are ionic clays in South China and Myanmar. Granites in this subtropical climate have been subjected to weakly acidic meteoric waters which become more acidic upon percolation through humus-rich topsoil. The granites break down into primary mineral grains which in turn chemically weather and release rare earth cations into the acidic groundwater percolating downward through the soil profile. The deposits are characterized by the clay mineral kaolinite,

TABLE 1.
The average abundance of elements in the Earth's crust.

Group	Rank	Element (criticals in bold)	Crustal Abundance	Units
Major Elements	1.	Oxygen	46.1	weight percent (%)
	2.	Silicon	28.2	
	3.	**Aluminum**	8.23	
	4.	Iron	5.63	
	5.	Calcium	4.15	
	6.	Sodium	2.36	
	7.	**Magnesium**	2.33	
	8.	Potassium	2.09	
	9.	**Titanium**	0.56	
	10.	Hydrogen	0.14	
	11.	Phosphorus	0.11	
Minor Elements	12.	**Manganese**	950	parts per million (ppm)
	13.	Fluorine	585	
	14.	**Barium**	425	
	15.	Strontium	370	
	16.	Sulfur	350	
	17.	Carbon	200	
	18.	**Zirconium**	165	
	19.	Chlorine	145	
	20.	**Vanadium**	120	
	21.	**Chromium**	102	
Trace Elements	22.	**Rubidium**	90	
	23.	**Nickel**	84	
	24.	**Zinc**	70	
	25.	**Cerium** (Rare Earth Element)	66.5	
	26.	Copper	60	
	27.	**Neodymium** (Rare Earth Element)	41.5	
	28.	**Lanthanum** (Rare Earth Element)	39	
	29.	**Yttrium** (Rare Earth Element)	33	
	30.	**Cobalt**	25	
	31.	**Scandium** (Rare Earth Element)	22	
	32.	**Lithium**	20	
	33.	**Niobium**	20	
	34.	Nitrogen	19	
	35.	**Gallium**	19	
	36.	Lead	14	
	37.	Boron	10	
	38.	Thorium	9.6	
	39.	**Praseodymium** (Rare Earth Element)	9.2	
	40.	**Samarium** (Rare Earth Element)	7.05	
	41.	**Gadolinium** (Rare Earth Element)	6.2	
	42.	**Dysprosium** (Rare Earth Element)	5.2	
	43.	Argon	3.5	
	44.	**Erbium** (Rare Earth Element)	3.5	
	45.	**Ytterbium** (Rare Earth Element)	3.2	
	46.	**Cesium**	3	
	47.	**Hafnium**	3.0	
	48.	**Beryllium**	2.8	
	49.	Uranium	2.7	
	50.	Bromine	2.4	
	51.	**Tin**	2.3	
	52.	**Europium** (Rare Earth Element)	2.0	
	53.	**Tantalum**	2.0	
	54.	**Arsenic**	1.8	
	55.	**Germanium**	1.5	
	56.	**Holmium** (Rare Earth Element)	1.3	
	57.	**Tungsten**	1.25	
	58.	Molybdenum	1.2	
	59.	**Terbium** (Rare Earth Element)	1.2	
	60.	Thallium	850	parts per billion (ppb)
	61.	**Lutetium** (Rare Earth Element)	800	
	62.	**Thulium** (Rare Earth Element)	520	
	63.	Iodide	450	
	64.	**Indium**	250	
	65.	**Antimony**	200	
	66.	Cadmium	150	
	67.	Mercury	85	
	68.	Silver	75	
	69.	Selenium	50	
	70.	**Palladium**	15	
	71.	**Bismuth**	8.5	
	72.	Helium	8	
	73.	Neon	5	
	74.	**Platinum**	5	
	75.	Gold	4	
	76.	Osmium	1.5	
	77-118.	Others under 1 ppb		

(Source: CRC, 2008)

a byproduct of weathering aluminosilicate minerals like feldspar. The positively charged rare earth cations, 50% or more of which are the heavy elements, stick to the negatively charged surfaces of the clays but are easy to wash back into solution, which is why this deposit is economic at grades as low as 500 ppm (Bao and Zhao, 2008).

Organic matter can also "catch" rare earths and other elements from descending groundwater. Coal, in particular low rank "brown coal" like lignite, contains oxygen function groups and sites for bonding cations as they infiltrate through. Coal can also contain rare earths in the form of tiny grains of primary minerals from clay and silt that washed or blew into the swamp, but it's the organically bound elements that are easiest to extract. Leaching experiments on rare earth-enriched North Dakota lignite at the University of North Dakota College of Engineering & Mines Research Institute (CEMRI) shows that the elements are indeed mostly organically associated and therefore weakly held within the coal and simple (cheap) to extract (Laudal et al., 2018). Gallium and germanium are two other top candidates that could one day be commercially produced alongside rare earths from lignite in the U.S. Gallium, germanium, and the rare earths dysprosium, terbium, and scandium are some of the highest value commodities on the critical minerals list, with market prices in the range of $100 to $500 per pound.

The case for critical mineral production from lignite is simple: easy extraction of high value trace elements. They just need to be found in slightly elevated concentrations, or produced as a byproduct where mining costs are already covered. What does "slightly elevated" look like? The DOE's 300 ppm figure is probably less than twice the rare earth concentrations in the dirt below your feet right now, as the average abundance of rare earths in upper continental crust (rocks and sediment near the Earth's surface) is 182 ppm (McLennan, 2001). The important distinction is most of that is locked up in those resistant primary mineral grains, while in coal it is weakly bound to the organics. With the latest research showing how easy rare earths are removed from lignite, and the added value of gallium and germanium, CEMRI has evaluated that critical mineral extraction from lignite at an existing mine could be economic far below the 300 ppm rare earth element concentrations initially proposed by the DOE. To open a new mine or reopen an abandoned mine, concentrations might need to be somewhat higher. Double the "average" upper crustal abundance is a good place to start, with anything over 364 ppm considered enriched (Dai et al, 2015).

CONDITIONS FOR ENRICHMENT IN NORTH DAKOTA

While granitic bedrock in South China has been weathering into the world's foremost heavy rare earth deposit, the sandstones, siltstones, mudstones, and claystones near the surface of southwestern North Dakota have also been leaching their rare earth elements. Part I described the phenomena where lignites near the tops of buttes often contain elevated rare earth element concentrations. Although spot concentrations of lignites in these settings can exceed 1,000 ppm rare earths, on par with the clay deposits in South China, the zones of enrichment are only a few inches thick; far thinner than the clay deposits mined overseas, which can be over 30 feet thick. Part of the discrepancy is due to the parent materials. The clays in South China formed as concentrated weathering products from granites that contained roughly 200 to 300 ppm rare earth elements (Li et al., 2017), while clastic sedimentary rocks in North Dakota are likely much closer to average upper continental crust (182 ppm). The more important factor is the climate.

Rare earths and other critical elements are mobilized by acidic waters, and the most acidic soils are found under lush vegetation where the climate is warm and wet. Long-term landscapes subjected to subtropical climates are required to naturally break down the plethora of different rare earth bearing mineral grains and concentrate them in coals or ionic clays below. Some uplands in southwestern North Dakota could have been weathering for hundreds of thousands, if not millions of years, but the climate has been anything but subtropical during that period. Glaciers may have been visible on the northeastern horizon at points during the Quaternary, which includes the last ice age starting 2.58 million years ago. A much warmer and wetter climate would be required to weather large volumes of sediment intensely enough to produce thicker zones of significant rare earth enrichment. Fortunately, the climate of North Dakota's more distant past was far less temperate.

THE BEAR DEN AND RHAME BED WEATHERING PROFILES

Exposures across the central part of western North Dakota preserve the record of one of the warmest and wettest climate events in Earth history, the Paleocene-Eocene thermal maximum, which occurred approximately 56 million years ago. The acidic waters that percolated through the soil profile during this period intensely weathered the feldspar and smectite-rich sediments to form a thick sequence of kaolinite, which primarily appears today as a bright white bed with orange iron staining that is easily traced across Dunn, Stark, and adjacent portions of the surrounding counties (fig. 1). Another thick interval of bright, kaolinized sediment called the Rhame bed occurs 1,000 feet lower in the stratigraphic column. It represents the uppermost portion of Slope Formation, marking the contact with the overlying Bullion Creek Formation. This weathering zone is older, having formed around 62 million years ago, outcropping today across Golden Valley, Slope, Bowman, Hettinger, Grant, and Morton counties.

The two weathering profiles are broadly analogous; both typically vary from 15 to 30 feet thick, are brightly colored due to leaching (figs. 2 and 3), rich in kaolinite, and often contain pedogenic silcretes. The Bear Den has been formalized as a member of the Golden Valley Formation (Hickey, 1977), but the Rhame has been referred to as a bed (Wehrfritz, 1978) despite it often containing multiple beds of sandstone, siltstone, mudstone, claystone, or lignite within it. It is probably more appropriate to consider the Rhame a zone, although it is thick, widespread, and consistent enough that we are considering it for elevation to member status.

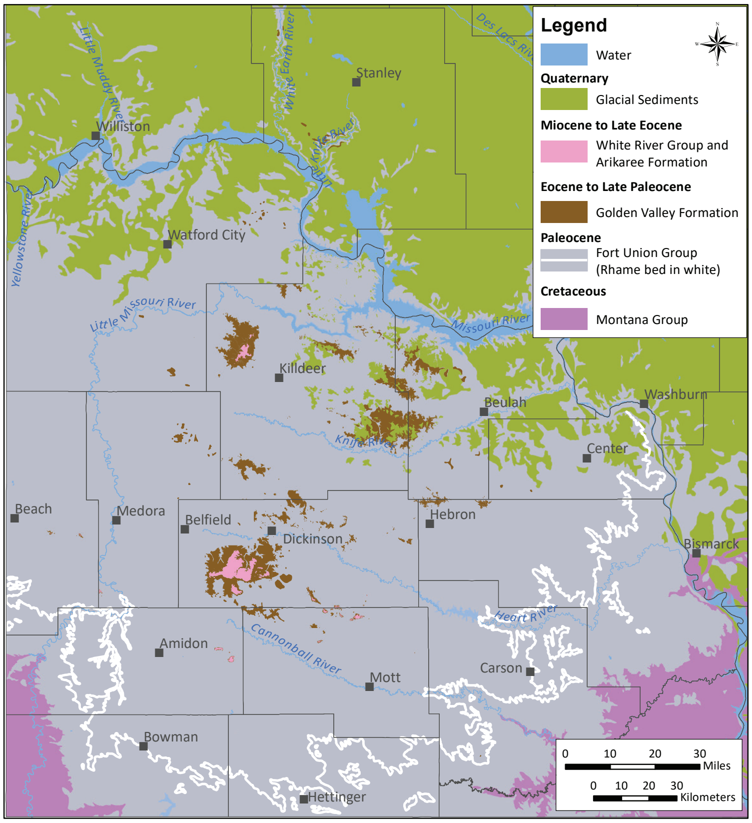

FIGURE 1.
The generalized surface geology of western North Dakota. The Bear Den Member occurs at the base of the Golden Valley Formation along the contact with the underlying Fort Union Group. Geology modified from Clayton and others (1980), with additional data from the NDGS 24K surface geology map series.

FIGURE 2.
The Bear Den Member of the Golden Valley Formation outcrops in southwestern Dunn County.

FIGURE 3.
The Rhame bed outcrops in north-central Slope County.

The Bear Den Member has been well studied as it represents one of the most detailed records of one of Earth's most significant climate events (Harrington et al., 2005; Clechenko et al., 2007). Large injections of carbon into the atmosphere, likely from volcanism in the North Atlantic, caused abrupt warming across the globe. Temperatures within the interior U.S. were already much warmer than today but rose another 5°C (9°F) for a period of up to 200,000 years (Wing et al., 2005; Murphy et al., 2010). The Rhame bed has been studied in less detail, but there is no known global thermal event known to have occurred between 61 and 63 million years ago, suggesting instead that it represents an extended pause in deposition. The relatively short, high intensity weathering of the Bear Den verses the longer, more moderate weathering of the Rhame bed produced remarkably similar profiles.

Both weathering zones have historically been the subject of mineral exploration, but for the clay itself, and not the critical minerals below. Kaolinite is commonly known as "pottery clay," and both the Bear Den Member and Rhame bed have been utilized in the state for the manufacture of ceramics (Murphy, 1995). A brick and tile plant operated just to the north of the town of Hettinger from the late 1930s through the mid-1960s that likely utilized the Rhame bed, and the Hebron Brick plant still mines the Bear Den Member today. The Fargodome and many other brick structures in the state are built with clays from fossil soils formed during a far more tropical, ancient North Dakota.

THE NDGS INVESTIGATES (PART II)

The North Dakota Geological Survey examined these weathering zones in the early 2010s, this time for their alumina contents. Aluminum is an immobile element that is concentrated as other elements are leached away by weathering. Murphy (2013) evaluated both horizons to determine the suitability of manufacturing ceramic proppant from these kaolinite-rich units, finding individual samples contained up to 34% alumina in the Bear Den Member and 27% in the Rhame bed. He also used X-ray diffraction to collect data on many other elements which a few years later would be classified as critical to the national security of the United States. Murphy reported enrichment in arsenic, cobalt, hafnium, magnesium, nickel, and titanium in some clay samples. Also included in this report were analyses of one rare earth element, yttrium, which were generally low (around 15 ppm), but Murphy targeted the most intensely weathered sediment which contained the most residual aluminum and had little reason to look lower in the profile for where the other mobile trace elements leached to. By 2015, rare earth production from coal had become a topic of national interest, and the NDGS began its broad-based characterization study of North Dakota lignites (Kruger, 2015).

Five years and over 1,000 lignite samples later, the NDGS had found some promising rare earth concentrations scattered across the southwestern part of the state, but a cohesive exploration model was still elusive. It seemed apparent that long-term, low-intensity weathering of stable uplands could produce slight, thin enrichment in the coals below, but this model could not explain the seemingly random, higher-grade enrichment seen in some coals that were not associated with uplands. An 18-inch-thick lignite in the Logging Camp Ranch area of Slope County was especially perplexing, as two or three thick coals (the Harmon, Hanson, and H lignites) occurred above it and were not enriched. Outcrops of the Bear Den and Rhame bed had been investigated, but early sites didn't contain well developed lignites and the organic-rich mudstones sampled were only slightly enriched.

In August of 2021, the NDGS was looking to round out the stratigraphic and geographic distribution of our lignite sampling and visited outcrops in Dunn and Stark counties, two of which contained lignites within the Bear Den Member. Samples from these two outcrops, representing the same interval over 50 miles apart, collected within a few hours of each other, were some of the highest rare earth concentrations seen in seven years of sampling (fig. 4). This included the first sample of significantly enriched coal during the project (defined as ten times the average concentrations of the upper continental crust, or over 1,820 ppm rare earth elements). 2022 was marked by visits to another 15 outcrops where the Bear Den was exposed. By combining all of the sample results from these locations on a composite stratigraphic column (fig. 5), a clear picture emerges: maximum enrichment near the base of the weathering zone, consistent with what would be expected in a model involving critical element mobilization within an ancient weathering profile. More significantly enriched samples were found, as high as 2,570 ppm rare earths at the Hebron Brick Company pit (Murphy et al., 2023).

These elevated concentrations also prompted more intense investigation of the Rhame bed. Although several previous mappers had suggested it was not exposed in the Logging Camp Ranch area, the NDGS was able to correlate it northeastward where it is often very subtle in appearance. It was found that the Rhame bed directly overlies the enriched lignite in that area, explaining how it could have become so enriched while the coals above it (deposited after the Rhame bed weathered) were not. Extensive lateral sampling of this lignite produced 15 enriched samples (over 910 ppm rare earth elements) and three significantly enriched samples, as high as 2,792 ppm in the same relative position as the enriched Bear Den samples, ie., at the base of the weathering profile.

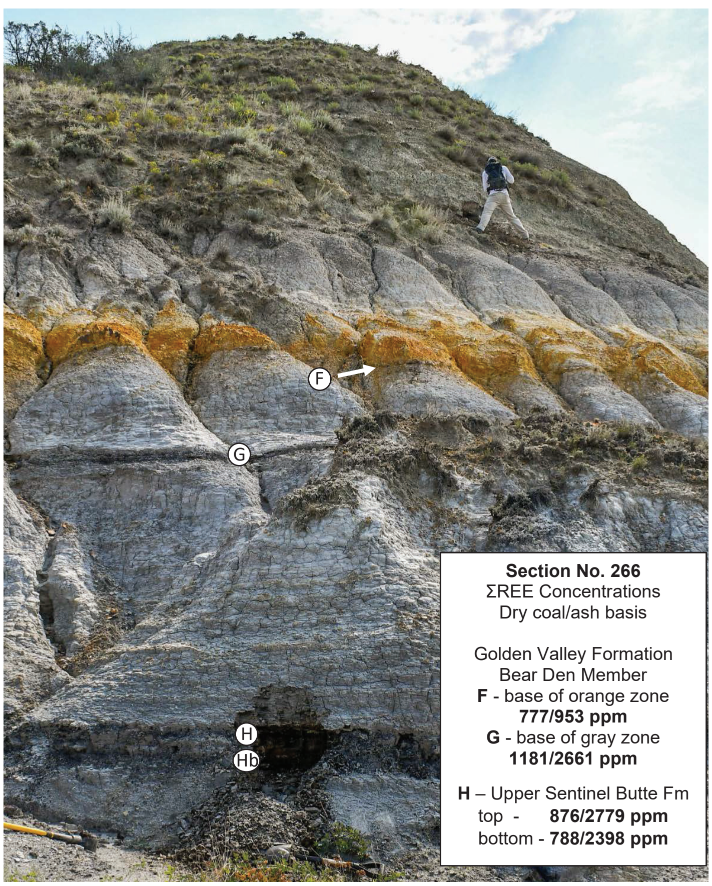

FIGURE 4.
Sampling the Bear Den Member and uppermost Sentinel Butte Formation in southwestern Dunn County in August 2021. Four samples from three thin lignites in the lower part of the weathering profile contained total rare earth element (ΣREE) concentrations averaging 903 ppm, nearly 5 times higher than average rocks and sediment near the Earth's surface.

WHAT TO DO WITH AN EXPLORATION MODEL

The 1,706 NDGS samples analyzed so far would only be a tiny fraction of what would be required to characterize the rare earth contents of North Dakota's lignites via randomized sampling. Now that we have a somewhat cohesive explanation for the rare earth element distribution in the Williston Basin, we are able to narrow down exploration within the 1,800 feet of lignite-bearing rock to two 30-foot intervals that should contain the most enrichment. This is still a very large area. The Bear Den Member, despite being mostly eroded away, is still present over approximately 340 square miles of the state, often within 100 feet or less of the surface and easily explored through drilling. The Rhame bed is more difficult to quantify, but its area is likely several times more than that of the Bear Den Member. It underlies most of the western half of the state and is well exposed and well-developed along the southern rim of the basin, but it is buried by several hundred feet of younger sedimentary rock in middle portions of the basin and obscured by glacial cover where it would outcrop along the northern rim. Despite this, there are hundreds, likely thousands, of yet unexplored outcrops of these two horizons and certainly thousands of fields and pastures where they are present just below the surface.

The expansive nature of these weathered rocks is important if the underlying lignites are ever to one day be commercial targets for critical mineral production. Over much of that area there will be no lignites present below the weathered horizon to uptake the critical minerals as they infiltrated the profile. In other areas lignites will be present but in positions too low for the critical mineral-bearing acidic waters to have reached them, or they were too high and leached away themselves. The most promising possible outcome of exploration is to find a thick, well-developed lignite in the perfect position, just below the base of a strongly weathered profile. Just how much rare earth content should such a coal accommodate? That question remains unanswered, but a nearly optimal example in southeastern Golden Valley County provides some clues. A 17-inch-thick lignite is fairly well-developed below 12 feet of brightly-colored claystone, mudstone, and siltstone, representing the Rhame bed weathering zone (fig. 6). The upper 6.5 inches of lignite are significantly enriched in rare earth elements, and the bottom of the bed is still 653 ppm, 10 times higher than the average U.S. coal (66 ppm; Finkelman, 1993).

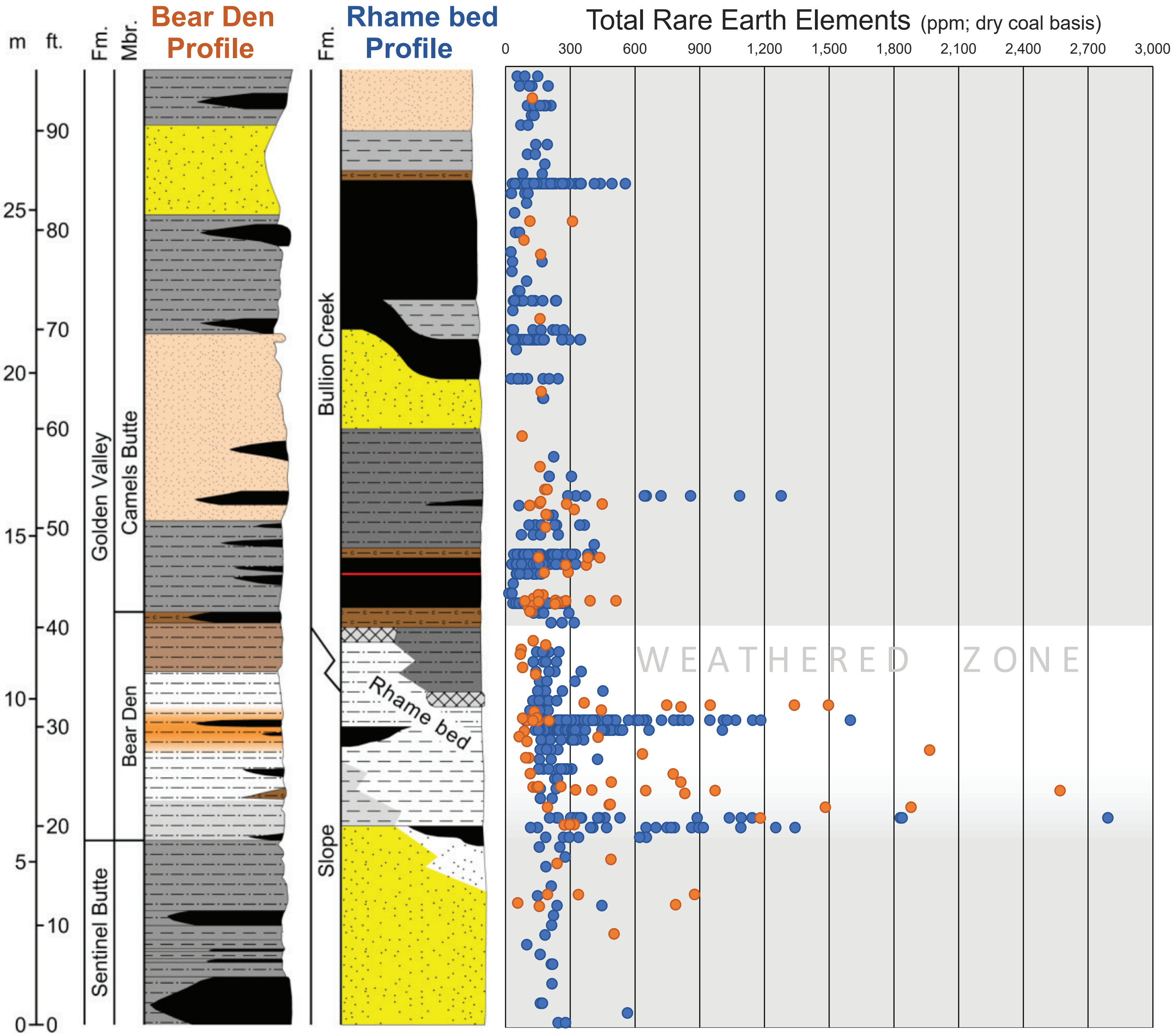

FIGURE 5.

Generic stratigraphic columns of the lower Golden Valley and upper Sentinel Butte Formations (left) and lower Bullion Creek and upper Slope Formations (right). Samples from over 100 sites across southwestern North Dakota are plotted with their rare earth element concentrations, showing enrichment in lignites positioned below the weathered portion of these two profiles. Samples from the Bear Den and Rhame bed profiles are represented by orange and blue dots, respectively (modified from Murphy et al., 2023 and Moxness et al., 2023).

Does the enrichment all the way through the lignite imply some of the weathered rare earths continued downward and dispersed through the underlying profile? If the lignite had been thicker, it would have been enriched at two feet? Three feet? The NDGS continues its exploration to find thicker coals in these settings, as it's difficult to imagine mining a bed only 17 inches thick, especially in rugged badlands terrain, even if it contains some of the highest concentrations reported in the nation. Still, coal 17 inches thick averaging 1,150 ppm contains more rare earth content than five feet of coal at 300 ppm, with less material handling.

The specifics of exactly how thick and how enriched a coal would need to be in order to be developed solely for its critical mineral contents is still speculative, as no one has commercially produced rare earths from lignite before. The U.S. DOE continues its effort to realize critical mineral production from coal-based feedstocks, and there is real potential for an extraction plant to be built in North Dakota in the coming years (Grand Forks Herald, 2023). It makes the most sense to scale this technology at North Dakota's existing lignite mines, where low concentrations are offset by low mining costs, but once the extraction technology is commercialized, the economics of highly-enriched lignites nearby will become much less cloudy, and we will better understand the prospects for these unique coal seams to contribute to the national security of the United States.

FIGURE 6. Sampling a 17-inch-thick lignite below the Rhame bed in southeastern Golden Valley County. Sample locations and total rare earth element (REE) concentrations plotted on the right.

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Review of the 2023 ROCKY MOUNTAIN SECTION AAPG ANNUAL MEETING IN BISMARCK, NORTH DAKOTA

BY TIMOTHY O. NESHEIM

INTRODUCTION

The Rocky Mountain Section of the American Association of Petroleum Geologists (RMS-AAPG) annual meeting was held in Bismarck, North Dakota for the first time in 35 years. This meeting was initially prompted in 2019 by the Rocky Mountain Section of the Geological Society of America (GSA), who approached the RMS-AAPG to co-host a meeting in North Dakota during 2023. However, the ensuing global Covid-19 pandemic shifted the timings of both organizational annual meetings, and the 2023 meeting became a standalone RMS-AAPG event. Between the 35-year hiatus of running an RMS-AAPG meeting in North Dakota and multiple Covid-19 ripple effects, there were many questions about this 2023 meeting.

WHAT IS THE ROCKY MOUNTAIN SECTION?

The Rocky Mountain Section AAPG is the loose affiliation of geological societies and associations spanning the Rocky Mountain region of the United States from New Mexico to North Dakota and Montana. The RMS-AAPG Annual Meeting rotates locations annually and over the past decade has been held in Grand Junction (CO), Salt Lake City (UT), Cheyenne (WY), Billings (MT), and Denver (CO). When the RMS-AAPG Annual Meeting is held in Denver, attendance is usually 600-800 people. Outside of Denver, attendance is usually on the order of a few hundred. The technical agenda of RMS-AAPG meetings usually has a strong petroleum geology base, but in recent years has been expanded to include non-petroleum topics such as geothermal and CCUS (carbon capture utilization and storage). Attendance of RMS-AAPG annual meetings is largely comprised of geologists from industry, government, and academia.

2023 MEETING AGENDA

The meeting theme, *Energy and Plains Solutions*, was meant to be a play on words that touched on the geographic location and a few of the main technical agenda components of the meeting. *Energy* was meant to encompass both the ongoing importance of oil and gas resources as well as growing efforts in geothermal energy. The unconventional Bakken oil play reshaped the economic and physical landscape of the greater Williston Basin area and was one key technical agenda component. Being held in North Dakota, this year's technical agenda had a Williston Basin focus, which is positioned in the northern Great Plains of North America. *Solutions* related to multiple carbon sequestration projects progressing in the plains of North Dakota (and beyond) to minimize CO_2 emissions. Additional technical material extended throughout the Rocky Mountain region, including multiple sessions on the Uinta Basin, and beyond.

PRE-MEETING SHORT COURSE AND CORE WORKSHOP

While the main portion of this meeting was June 4th-6th at the Bismarck Event Center, pre- and post-conference programming stretched for a full week from June 2nd to June 8th. The first official component tied to the conference was a short course on Friday, June 2nd led by retired geologist Bob Lindsay titled *"How to Describe a Core."* This short course was run with both in-person and virtual attendees (per request) and had 15 total attendees. Next, a two-day Williston Basin core workshop was run on Saturday-Sunday (June 3-4), which was attended by 45 people including registrants, sponsoring entities, and presenters. A total of 13 core-based presentations were run spanning the Cambrian (Deadwood Formation) to Permian (Broom Creek Formation) sedimentary units within the Williston Basin (fig. 1). The first workshop agenda day included core-based presentations on units including the Deadwood, Red River, Interlake, and Amsden Formations as well as the Mississippian Madison Group. The second day consisted exclusively of Bakken-Three Forks content, with core samples and presentation material spanning North Dakota, Saskatchewan, and Manitoba's portions of the prolific Bakken-Three Forks play.

FIGURE 1.
Dan Kohlruss (Saskatchewan Geological Survey) leading a core workshop session on the Bakken Formation from the Saskatchewan portion of the Williston Basin.

The core workshop included approximately 15 tons or 3,600 feet of core sample and stratigraphic units important to petroleum resources and carbon sequestration. Having served a pivotal role in the emergence of the Bakken unconventional oil play, many of the workshop presenters and attendees commented on the importance of the Wilson M. Laird Core & Sample Library which holds over 90 miles of core samples from North Dakota's subsurface.

MAIN CONFERENCE

The main conference began with an opening Icebreaker event in the conference exhibit hall Sunday night which was attended by approximately 130 registered people and provided an initial opportunity for attendees to network with one another as well as the 21 conference exhibitors. The meeting technical program kicked off on Monday morning during the single-track opening plenary session with Timothy Nesheim (RMS-AAPG President and General Chair of the meeting) providing a welcome to attendees with an overview of the RMS-AAPG and a Williston Basin geologic overview that touched on the main technical themes of the conference. By mid-morning, three concurrent presentation sessions were running covering a variety of geologic and/or economic themes.

The technical program consisted of more than 85 oral and poster presentations on various topics including numerous petroleum geology-related topics from across the Rocky Mountain region with a Williston Basin focus. Additionally, there were more than thirty Energy Transition abstracts including CCUS (10), geothermal (11), critical minerals/Li (8), and hydrogen storage (4). Many attendees consistently commented very positively on the strong quality, quantity, and diversity of presentation topics.

By Tuesday morning, the final day of the 2023 RMS-AAPG annual meeting, the total registration/attendance of the conference had grown to over 200 people. Technical presentations continued through late Tuesday afternoon and closed with a single-track session titled "The Bakken After Action Report." This final session looked back at the early years of the prolific Bakken unconventional petroleum play which re-shaped the Williston Basin.

The energy and engagement of the attendees throughout the meeting was exceptionally strong from start to finish. The opening plenary Monday morning was strongly attended with standing room only (140 seats). Both keynote luncheon events on Monday and Tuesday (fig. 2), the Monday night museum social/RMS awards ceremony (fig. 3), and the Tuesday Presidents Reception had very strong turnouts of 60-70 attendees, which is a very high turnout for a conference of approximately 200 people. Even the final presentation of the closing session late Tuesday afternoon still held a solid attendance of approximately 50 people.

POST-MEETING FIELD TRIP

Following the conference, Levi Moxness (North Dakota Geological Survey) led a two-day field trip through the Little Missouri Badlands of western North Dakota. Starting at the Cretaceous/Paleogene contact (dinosaur extinction event),

FIGURE 2.
Tuesday luncheon featuring a keynote presentation by Kathy Neset, reviewing her 40+ year professional history, most of which occurred in North Dakota.

FIGURE 3.
David Petty (left) receiving the Julie LeFever Award from the Rocky Mountain Section AAPG, received in part for his multi-decade publication and presentation history on the Mississippian Madison Group section within the Williston Basin. Timothy Nesheim (2023 RMS-AAPG President and General Chair) is pictured on the right.

this post-conference field trip provided an overview of North Dakota's pre-glacial stratigraphy and geologic history. Key field trip stops included Mud Buttes (Cretaceous Hell Creek and Paleogene Ludlow Formations), Logging Camp Ranch (coal-bearing Bullion Creek Formation), and the Petrified Forest within the Theodore Roosevelt National Park. Multiple field trip highlights included numerous dynamic discussions around outcrops, pushing one of the vans up a hill near the Logging Camp Ranch stop, and exploring for and collecting Oligocene fossils at the Fitterer Ranch.

CLOSING COMMENTS

RMS-AAPG Annual Meetings have expanded in recent years to not only include petroleum resource technical focus, but also non-petroleum resources as well. The 2023 RMS-AAPG meeting touched on numerous non-petroleum components including coal, potash, geothermal, lithium, and other critical elements/minerals, and carbon sequence storage targets. The upcoming RMS-AAPG Annual Meeting will be in Utah during the fall of 2024 and will look to continue to build on the success of the recent meeting in Bismarck!

HOMES ON STILTS:

FARGO AREA CITIZENS FACE CONTINUED RESIDENTIAL FOUNDATION STABILITY ISSUES

BY FRED J. ANDERSON

The cities of Fargo and West Fargo lie on top of the former lakebed of the expansive Glacial Lake Agassiz. The lakebed sediments that were deposited offshore in the areas of quieter water in the lake are laminated silty clays and soft expansive clays of the Brenna and overlying Sherack Formations. At the interface of these two units, when the deposition of lake sediments was halted for a brief period in the late Holocene, ancient rivers flowed across the Lake Agassiz plain and incised their way into the Brenna Formation clays. Over time deposition of lake sediments resumed and the laminated silts and clays of the Sherack Formation were laid down over the Brenna clays and the glaciofluvial sediments (formally called the Poplar River Formation) sandwiching these channel sands between the two clay units. When these units are saturated, they can have a "quick" component and can flow when placed under a load from the surface. Because of these potentially unstable conditions (fig. 1), some residents in Fargo have been forced to effectively elevate their residential foundations. This is done by advancing long piers or piles into the shallow subsurface to find an adequate load-bearing layer, sometimes as deep as 90 feet or more. The load-bearing layer is generally the first stable glacial till or boulder clay.

FIGURE 1.
A Fargo residence where foundation subsidence has occurred. This photograph was taken over 30 years ago, and the entire home can be seen tilting towards the backyard (Photo from NDSU Professor Emeritus Dr. Don Schwert, 1991). The slab foundation of this house is dipping about 5° towards the backyard.

The City of Fargo does not currently track residences that end up needing building permits for installing bracing piers to stabilize their sinking foundations. However, the City of West Fargo does track such information and from that, some interesting insights can be gained from the spatial relationship of the location of these homes that have required stabilization (fig. 2).

In West Fargo several of the homes that have required stabilization are located within topographically low areas to the west and east of the Sheyenne River (fig. 2). It is supposed that when water levels are high in the Sheyenne River the local water table is also very shallow, perhaps just a few feet below land surface. The localized high-water table keeps the laminated silts and clays of the Sherack Formation saturated and less able to bear the surface loads from homes placed upon it. The soft and expansive (i.e., smectitic) underlying lake clays of the Brenna Formation also add to this stability problem (fig 3).

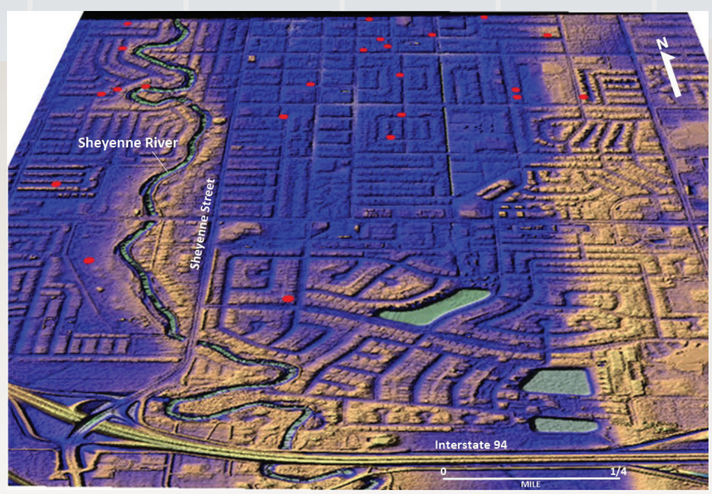


FIGURE 2.
Locations of homes in West Fargo (red dots) where foundation bracing has been implemented as a remedial measure to stabilize sinking foundations. As seen in this 3D LiDAR-based surface model all locations are located within localized low areas (shown in blue) presumably where shallow groundwater creates weaker clayey soil conditions between and within the Sherack and Brenna Formations.

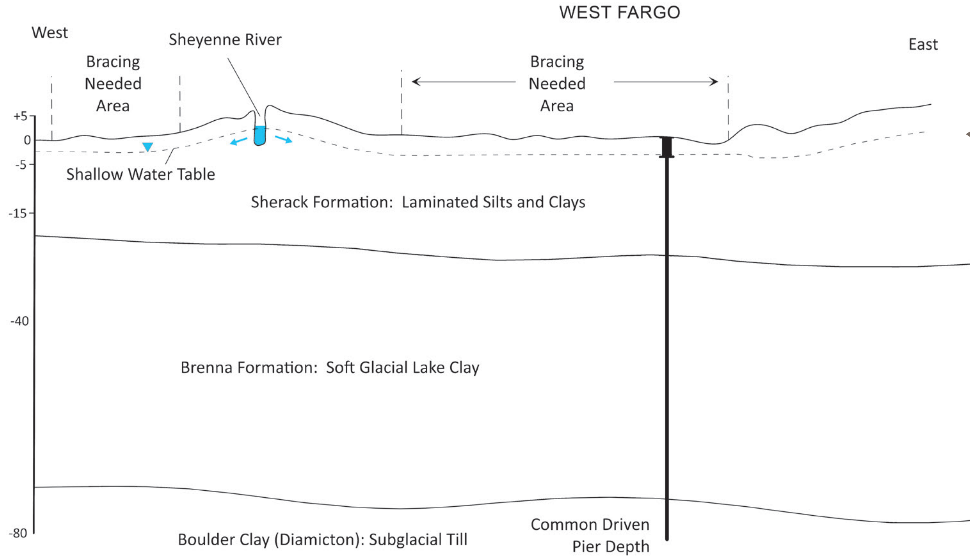


FIGURE 3.
Conceptual depiction of the shallow hydrogeologic conditions occurring in the West Fargo area between Sheyenne Street and 9th Street East. Surface topography modeled from available LiDAR data. Drilling records for this area do not show any shallow sands of the Poplar River Formation occurring in the shallow subsurface. Only the offshore glaciolacustrine silts and clays of the Sherack and Brenna Formations are described in this area.

Recently a homeowner contacted our offices about information related to this condition as they had been experiencing continued problems (figs. 4a and 4b) with a tilting and subsiding foundation. The problem had required repeated costly foundation stabilizing pier installations all around the base of the home (fig. 5). Costs for these kinds of remedial measures are often in the tens of thousands of dollars.

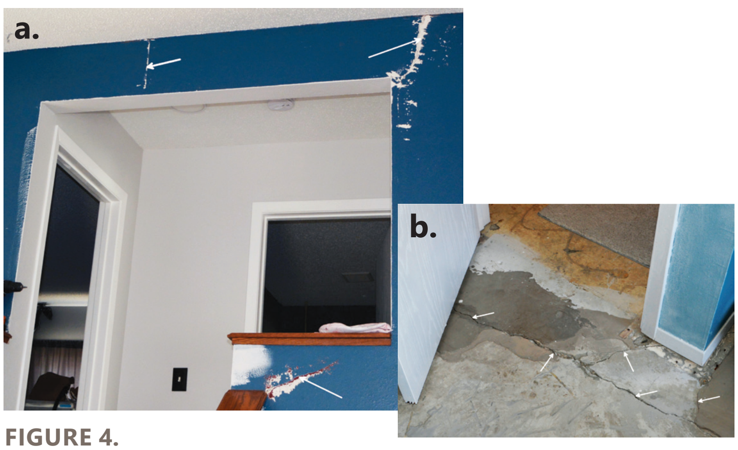


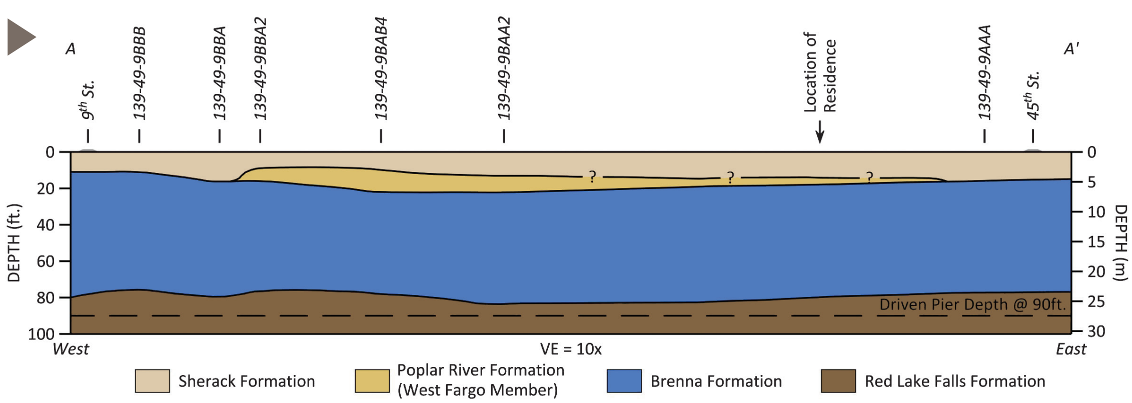
FIGURE 4.
Continual structural damage (shown at the locations of the white arrows) occurring within a northeast West Fargo home as the result of weak soil conditions. Cracks in the walls **(a.)** and basement slabs **(b.)** are found throughout this residence which has had several driven piers placed around the outside of the foundation in an attempt to stabilize the residence.

Glaciofluvial compaction ridges are found throughout the southern Red River Valley and in the greater Fargo area (fig. 6). These shallow sand bodies are the remnants of ancient rivers that flowed across the floor of a drained Glacial Lake Agassiz. Once the lake flooded again, additional lake sediments were deposited above these ridges which effectively "sandwiched" these deposits between the offshore clays (fig. 7).

From the regional perspective, the offshore silts and clays of the Brenna Formation are somewhat less extensive laterally in the Grand Forks area and slightly thinner, around 30 feet. In the Fargo area these soft lake clays are commonly around 70 feet thick, and much more laterally extensive (fig. 8). The Brenna Formation does, however, get dramatically thicker starting between Grafton and Drayton and on towards the border between Canada and the U.S. where it reaches its maximum thickness of over 110 feet.

Occurring together or separately (i.e., the compaction ridges and soft offshore lake sediments) these shallow geologic conditions will most likely continue to be problematic as rapid urban growth continues in both Fargo and Grand Forks. Sometimes, the rush to complete construction can lead to poor land preparation practices such as the filling in of old drainages and depressions that may have conveyed or contained water or saturated soils with poor quality or improperly placed backfill (fig 9).

FIGURE 5.
West to east cross-section of the shallow geologic units present in northwestern Fargo between 5th Street and 45th Street. Compaction ridge sediments of the West Fargo Member of the Poplar River Formation are present in this area of West Fargo and may extend for a considerable distance beneath the locations of homes where foundation settlement and stabilization have occurred.



It is also likely that the number of homeowners that have experienced these issues is much larger than what is currently known. Additional geologic investigations will likely be needed to better characterize the relationships and extent of these potentially problematic deposits that occur in our rapidly expanding urban environments in the Red River Valley.

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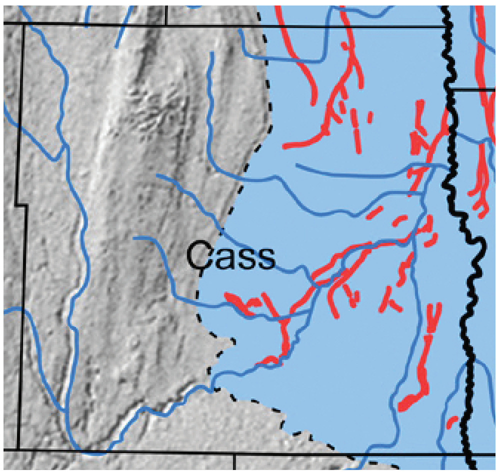

FIGURE 6. Approximate extent of offshore lake deposits of Glacial Lake Agassiz (shaded light blue) in Cass County, North Dakota, and location of mapped glaciofluvial compaction ridges (shown in red). As detailed geologic mapping work continues in this area more of these types of features are being discovered since incorporating LiDAR surface models into the geologic mapping workflow (modified from Harris and others, 2020).

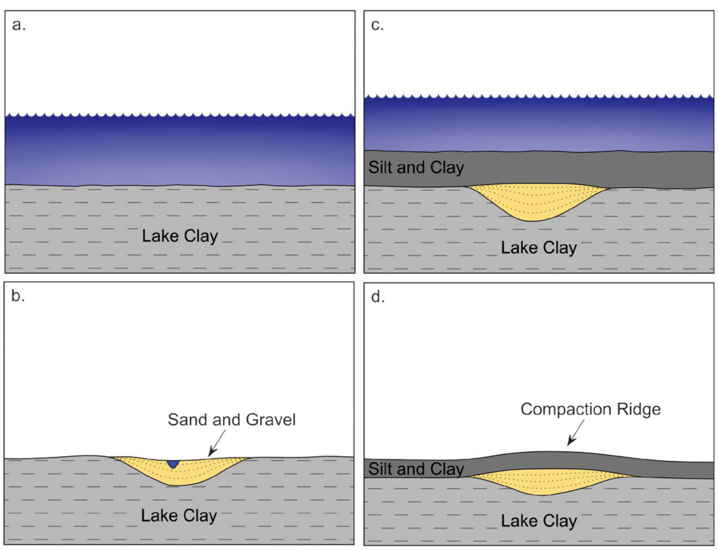

FIGURE 7. Steps in the formation of a glaciofluvial compaction ridge on the former Glacial Lake Agassiz plain. Fine-grained clays (i.e. the Brenna Formation) are deposited in the offshore quiet waters (a.), once the ice retreats and the lake drains, the lake plain is exposed and shallow rivers and streams begin to flow across the lake plain towards the northeast incising into the former lake bottom (b.), the lake returns with the readvance of glacial ice and additional offshore lake deposits of the Sherack Formation are deposited (c.), followed by the final retreat of ice and lake drainage, dewatering of the lake bottom and subsidence of the land surface leaving the remaining compaction ridges as slightly elevated linear expressions (d.) on the landscape. These features when saturated can exhibit a "quick" component and be capable of flow in the shallow subsurface.

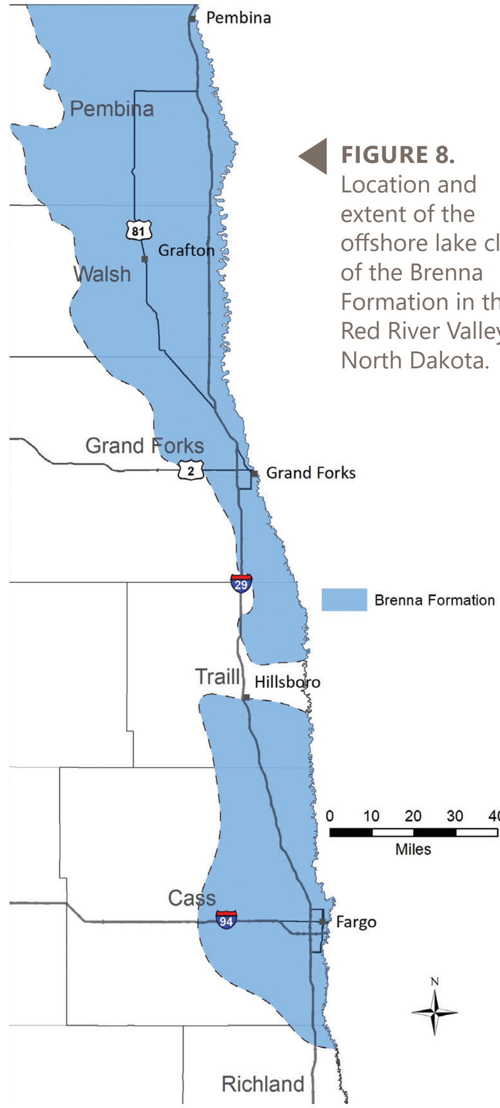

FIGURE 8. Location and extent of the offshore lake clays of the Brenna Formation in the Red River Valley of North Dakota.

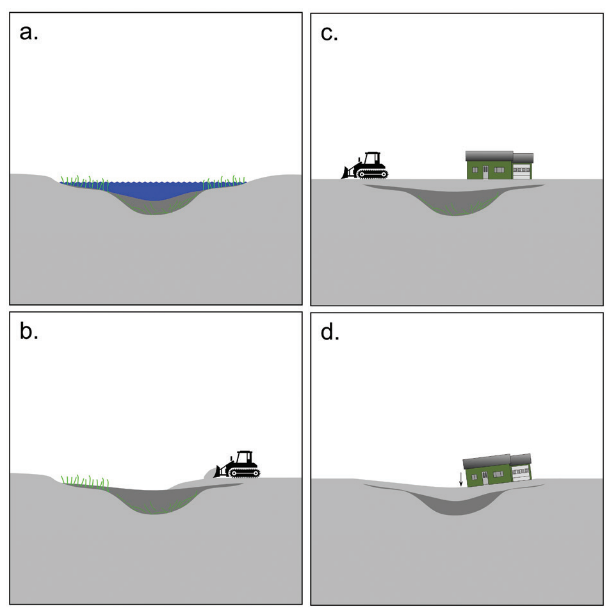

FIGURE 9. Filling in drainages or old ponds and sloughs with improperly placed backfill can result in poor foundation conditions for residential development. Former drainage area prior to residential development (a), filling in old drainage or depression (b), construction above filled area (c), subsidence of structures over time as filled area dewaters and compacts (d).

PRESERVING 45 YEARS OF PHOTOGRAPHS OF WESTERN NORTH DAKOTA

BY EDWARD C. MURPHY

I began working for the North Dakota Geological Survey as a temporary field inspector for the coal exploration program in June of 1977. The job was straight forward, but it did require me to quickly master the public land survey system (township, range, sections, quarter\quarter\quarter). I would typically spend Mondays in the office plotting coal exploration holes on maps and then take those maps into the field the rest of the workweek to field check the exploration holes for proper reclamation. My boss, Wes Norton, arranged for me to visit a coal exploration drilling site to see the size of the truck-mounted rig, portable mud pit, and the water truck so I could estimate the minimum area that was needed for a drill site and could better determine the likely location of an exploration hole (fig. 1). The hole, drilled by H & H Drilling out of Bowman, ND, was part of a multi-county coal exploration program managed by the ND Geological Survey and paid for by the U.S. Geological Survey. I searched through old files and found a photograph of that visit that I had not seen in 46 years. I was surprised but not shocked, since these things seem to happen in North Dakota, when I realized that two of the people in the photo are Slope County landowners (Kelly Lorge and Loren Jacobson) that recently gave us permission to take rock samples for our critical mineral project. I had not recalled that either Kelly or Loren had worked for H & H Drilling. The coal exploration permit program had begun two years earlier so there was a backlog of 7,000 test holes to field check across all 24 coal-bearing counties. The job provided an excellent opportunity to travel all over western North Dakota and to meet the farmers and ranchers on whose land the exploration had taken place.

FIGURE 1.
Ed Murphy (fifth from the left) inspecting the drilling of a coal exploration hole in Oliver County in 1977. Kelly Lorge is first from the left and Loren Jacobson is fourth from the left.

The first thing I did was to gather three or four dozen ND Geological Survey publications on the surface geology of western North Dakota. Foremost among them were the county geology reports (County Bulletins, Part 1). Those reports contain descriptions of the rocks and sediments present at the surface in each county along with black and white photographs of the prominent outcrops. Each report is accompanied by a surface geology map at a scale of 1:125,000. The resulting small library was housed in two field boxes that I kept in my field vehicle, a 1976 Plymouth Fury -- not the best vehicle for offroad driving. I plotted the highlighted outcrop locations on my field maps and read up on the surface geology of the area that I was working in. It was much easier to learn and retain things when you could match the outcrop photos and descriptions to the actual outcrops. However, color photographs would have been much easier to interpret because rock color is one of the primary distinguishing criteria between formations within the Fort Union Group. Little did I know that five years later my first mapping assignment would be to map the surface geology of the 44 USGS quadrangles that cover Dunn County, an area that I had thoroughly crisscrossed as a field inspector.

I quickly realized that the Kodak Instamatic camera I was using was not adequately capturing the geology as well as the scenic beauty of western North Dakota. Some of the best photographs that I had seen were in University of North Dakota geology seminars presented by professors Walter L. Moore and David B. Johnson. Both Walt and Dave used Nikon FM 35mm cameras along with Nikon 50mm and Vivitar Series 1, 70-210mm lenses. So, I bought that camera and those lenses along with a Nikon 18-55mm lens, the latter quickly became my main lens. It took me awhile to realize that there was more to taking pictures than just a good camera and lenses. In those days, you mailed the 35mm canister of film to one of Kodak's film processing centers

(925 Page Mill Road, Palo Alto, California is burned into my memory) and waited a week or so for the 35mm slides to come in. I primarily used Kodachrome because it was said to resist fading longer than any other color film. In 2005, twenty-six years and 445 rolls of film later (16,000 slides), I conceded that the days of 35mm film were numbered and reluctantly switched over to a Nikon digital single-lens reflex (SLR) camera (D7000, D7100, and eventually to a D7500). The cameras and lenses were similar in size, but the D7000 was lighter because it contained more plastic (fig. 2). The major advantage of digital over film was immediately knowing that you had captured a quality image. On the other hand, it eliminated the thrill and anticipation that came with the first opening of those yellow Kodak boxes to see the images you had captured.

It is difficult to convey geologic processes or concepts, especially to the nonscientific community, without using photographs, geologic maps, or illustrations. I have never forgotten how important the photographs in those geologic reports were to me in the late 1970s when I was trying to understand what was being said. For that reason, the articles that I have written and the presentations that I have given over the years contain an abundance of photographs. The majority of my photographs illustrate geologic features that were taken as part of specific projects. For example, I have taken 1,900 photographs in support of surface mapping projects and 1,100 photographs in support of a number of landslide projects. However, since I was often working in some of the most scenic areas in North Dakota, the badlands, major buttes, and other areas of rugged beauty in western North Dakota, I occasionally took photographs of the local scenery (figs. 3-6). Conversely, I find I did not take near as many photographs when I was working on oil and gas reserve pits, municipal garbage dumps, or wastewater

FIGURE 2.
The Nikon FM (on the right) and the Nikon D7000 have both performed well under trying field conditions. In the field, I typically just carry the camera, not the camera bag, slung over my shoulder. The Nikon FM was still going strong when I switched over to the D7000 despite being subjected to 26 years of dust, the sun's rays, constant jostling, and numerous droppings. Over the years, I went through several leather camera cases, camera bags, and numerous straps.

FIGURE 3.
Shadows stretch across Bullion Creek and Sentinel Butte strata at sunset in outcrops adjacent to East River Road north of the South Unit of the Theodore Roosevelt National Park in Billings County.

FIGURE 4.
The setting sun turned the clouds a pink hue in the Limber Pines Special Use Area in western Slope County. Photo taken looking to the east.

impoundments projects. Early on, I would photograph wildflowers, wildlife, sunrises and sunsets, lightning, rainbows, clouds, old farms and ranch buildings, and old windmills to augment my presentations, often ending a talk with a photograph of a sunset. Many of the old farm buildings and windmills I first encountered 45 years ago have long since disappeared. Additionally, since I have done fieldwork during all four seasons, I have documented all kinds of weather conditions; blizzards, hailstorms, lightning storms, tornadoes, windstorms, freezing rain, fog, unbearable heat, and in recent years, choking smoke from forest fires.

Most of my fieldwork was done alone, especially in the early years. As a result, very few of my photographs contain images of people, and since I was often working a half mile or more from my vehicle, few also contain images of field vehicles. Maybe that is why I find that some of the most intriguing photographs taken by A.G. Leonard in the early 1900s are those that include people dressed in the field clothes of the time along with images of saddled horses, teams of horses, or early automobiles.

I generated sixteen thousand 35mm slides in the 26 years between 1979 and 2005. These 35mm slides fill 41 three-ring binders that take up an entire 3x7 foot bookcase. I initially began by consecutively numbering my slides, but quit when the number approached 8,500 and switched to grouping my slides by either stratigraphic unit (e.g., Sentinel Butte Formation or Rhame bed) or locality (e.g., Killdeer Mountains or Logging Camp Ranch). I wrote cryptic notes, or better yet the public land survey system location, on the cardboard frames of many, but not all, of my slides. Approximately 12,000 of these slides have been digitally scanned, taking up 56 GB of memory. In the last 18 years, I have taken 22,500 digital photographs, adding 170 GB in images to my collection. I find it interesting that I averaged six hundred 35mm slides per year from 1979 to 2005 and 1,250 digital photographs per year from 2005 to present. Especially because there were numerous times when I took little or no digital photographs because I had photographed that locality years before. Additionally, the digital photography timeline roughly coincides with my time as State Geologist when administrative duties have curtailed some of my fieldwork. Several recent projects have likely somewhat skewed these numbers (6,400 photographs were taken as part of our critical minerals project from 2015 to the present and 1,800 photographs were taken during a ceramic proppant feasibility study in 2011).

With close to 40,000 photographs, it is likely not surprising that I have trouble finding specific images. I have always wanted to create a better filing system, but could never find the time to devote to it and instead just kept adding to the

FIGURE 5.
A double rainbow appears behind a windmill near the VVV Ranch in western Slope County.

problem with more images. Many of these photographs are preserved in the more than 500 PowerPoint presentations I have given in the last 20 years. In the Geological Survey, we took our time switching over from slide presentations to PowerPoint presentations because we determined that while the early PowerPoint projectors did a good job projecting graphs and figures, the projection quality of photographs was terrible. This problem went on for more than a decade, likely because most people's presentations did not contain a lot of photos. As a result, the Dept. of Mineral Resources purchased portable projectors and laptops in 2007 and to this day we carry our own projection system whenever and wherever we give a presentation.

At this point of my career, I find myself running out of time at the same time I am hoping to find the time to create a digital library of my photographs. The NDGS has never had a searchable photo library, but we have also never had tens of thousands of photographs, not to mention the 22,000 drone photographs we have generated in the last seven years. I am hoping to get these images into a system that will enable future geologists to quickly find them. Thus, saving them the time and expense of traveling to some of the more remote areas in western North Dakota to obtain an image. Although I for one could certainly understand why someone would want to experience the beauty of western North Dakota firsthand.

FIGURE 6.
An assortment of my photographs of western North Dakota.

FIGURE 6. continued.

BRUCE HICKS retires

In August of 1978, Bruce Hicks began working as a temporary employee for the North Dakota Geological Survey while a University of North Dakota student. Bruce graduated with a Petroleum Engineering degree in 1980 and then went to work full-time for the Geological Survey in the Bismarck office. In 1981, the Geological Survey's oil and gas regulatory portion was split off creating the Oil and Gas Division. Over the years Bruce held several positions including Water Injection Supervisor and Manager of Horizontal Drilling. For the last 24 years he served as the Assistant Director of the Oil and Gas Division and the last 18 years as an Assistant Director of the Dept. of Mineral Resources. At the end of June, Bruce retired after 45 years of dedicated service to the State of North Dakota.

Recent Geophysical Research

IDENTIFIES NORTH DAKOTA ELECTRICAL TRANSMISSION GRID AT RISK FROM POTENTIAL GEOMAGNETIC STORMS

Aurora Borealis as seen northeast of Linton in March 2023 (Moxness, NDGS)

BY FRED J. ANDERSON

Space weather phenomena such as geomagnetic storms have recently been shown to be potentially hazardous to the electrical infrastructure in the upper Midwest, particularly in eastern North Dakota and western Minnesota (fig. 1). Researchers with the U.S. Geological Survey's Geomagnetics Program in Boulder, Colorado completed a study in which it was shown that the electrical transmission grid in North Dakota (and neighboring Minnesota) could be highly susceptible to a geomagnetic storm of a scale anticipated to occur about once per century (Lucas et al., 2019). The study used data collected from ground-based geomagnetic monitoring stations and magnetotelluric sounding stations that were placed across the U.S., and in North Dakota in 2017-18 (fig. 2), as a part of the National Science Foundation's Earth Scope Program (Anderson, 2018).

The shallow depths and lithology of eastern North Dakota's crystalline basement rocks are more resistive to geomagnetically induced currents since they occur at shallower depths and are dominantly silica-rich lithologies of igneous and metamorphic origin. This makes the overlying electrical grid more susceptible to electrical current propagation from the geomagnetically induced currents

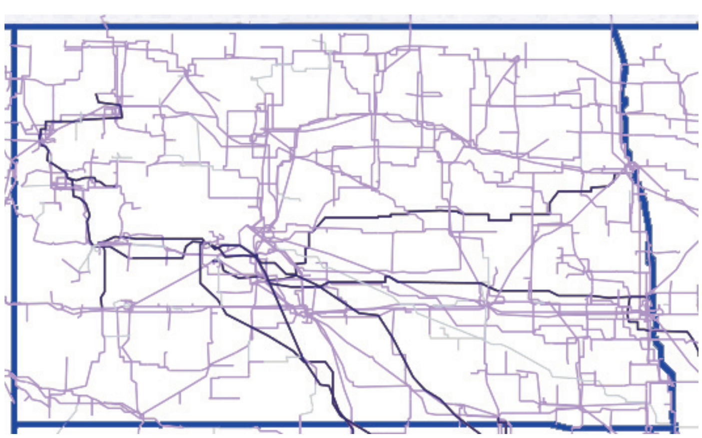

FIGURE 1.
The electrical transmission grid in North Dakota and western Minnesota (U.S. Energy Information Administration data, 2023). The darker lines are the larger 345 kV bulk electrical transmission lines. The grid is dense in central and eastern North Dakota.

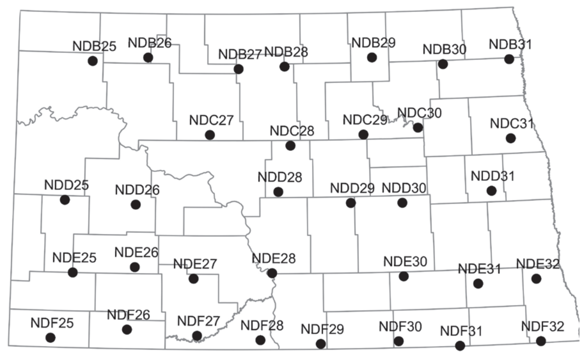

FIGURE 2.
Locations of NSF-EarthScope Magnetotelluric Array Sounding Stations in North Dakota that operated from Sept. 2017 to Sept. 2018. These stations were used to passively collect geophysical data on the geoelectrical properties of Earth created from space weather phenomena such as geomagnetic storms.

through the existing transmission lines since it is more difficult for the earth to absorb at these locations. Recent investigations by the USGS (Lucas, et. al, 2019) and modeling products created by NOAA's Space Weather Prediction Center (NOAA-SWPC, 2023) demonstrate this relationship (fig. 3). Plans and designs for new transmission lines in eastern North Dakota should take these factors into account.

Coronal mass ejections are created when the exceptionally strong magnetic fields on the sun abruptly realign and eject enormous amounts of solar material along with an accompanying strong magnetic field away from the sun. The coronal mass ejections become problematic when they travel along an intercept course with Earth's orbit.

These coronal mass ejections travel exceptionally fast from the sun to Earth and can arrive in just a few days traveling at a velocity of around 6.7 million miles per hour, which is about 1/100th of the speed of light. The solar wind is also buffeting Earth's magnetic field flowing past Earth at up to a million miles per hour (fig. 4).

We are approaching the next solar maximum in our current solar cycle, Solar Cycle 25, which is most likely to occur during the summer of 2025 (NASA, 2021). Updates from the NOAA SWPC reviewed during this writing forecast an even earlier arrival of the solar maximum in the summer of 2024! Although the anticipated solar maximum is estimated to be similar to the previous cycle and not significantly greater than average, the hazard from geomagnetic disturbances to the power grid remains a possibility.

When coronal mass ejections collide with the magnetic field of Earth they create geomagnetically induced currents that travel down the magnetic field lines and into Earth. These geomagnetically induced currents can travel along power lines and pipelines, creating overloads in the power grid and causing damages to transformers, resulting in large scale power blackouts. One of the more famous historical space weather events was the Carrington Event (named after Richard Carrington, an amateur sky observer in Redhill, England) which occurred in September of 1859 and set telegraph lines afire and resulted in an aurora seen around the world (Dobrijeciv and May, 2022). The Carrington Solar Storm is considered the largest on record. It is estimated that a Carrington-scale event occurring in today's electrified world would result in damages in the trillions of dollars.

At the time of this writing, the U.S. Energy Department's Grid Resilience State and Tribal Formula Grants program has awarded 7.5 million dollars to the state of North Dakota to upgrade the power grid and make it more resilient and reliable against extreme weather and natural hazards (Nicholson, 2023). Also, the North Dakota Department of Emergency Services and other supporting state agencies, including the NDGS, are currently updating the State's All Hazard Mitigation Plan. The plan includes the evaluation, planning, and mitigation of potential Space Weather Hazards.

With mitigation in mind, perhaps the construction of a new geomagnetic observatory station in North Dakota (fig. 5) would enhance the current capabilities of the existing array to collect important geomagnetic observations. This would support accurate analysis of the effects of these types of geophysical phenomena, in a current data sparse, but dense and susceptible region of electrical transmission capacity in the upper-Midwest.

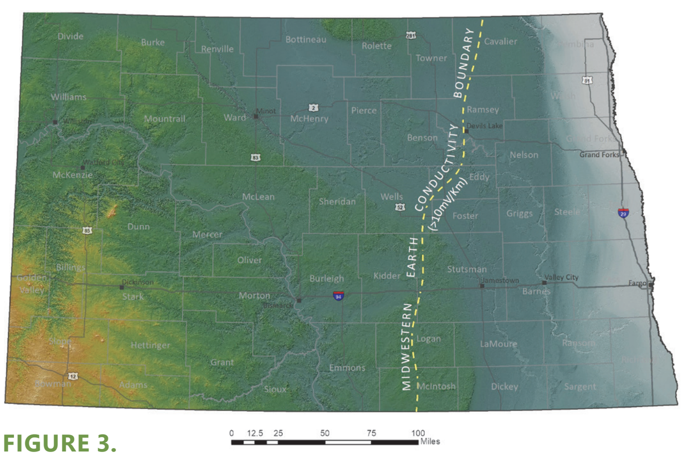

FIGURE 3.
Geophysical investigation and modeling by the USGS and NOAA's Space Weather Prediction Center show that eastern North Dakota has a higher susceptibility to geomagnetically induced currents. This is due to the shallower depth of more electrically resistant rocks in the eastern part of the state as opposed to the west.

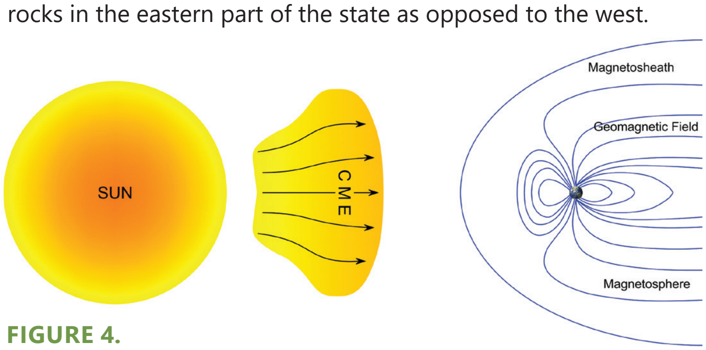

FIGURE 4.
Illustration of the relationships of the sun's influence on Earth's magnetic field.

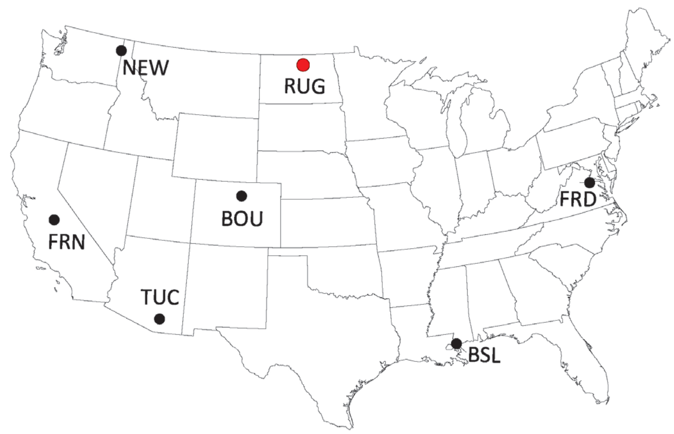

FIGURE 5.
Location of current geomagnetic observatory stations operated by the U.S. Geological Survey in the conterminous U.S. A new station in the upper Midwest, at Rugby, ND (RUG), could provide better geomagnetic field monitoring and increase the accuracy of regional geoelectrical hazard assessments. Current stations include Fresno, California (FRN), Newport, Washington (NEW), Tucson, Arizona (TUC), Boulder, Colorado (BOU), Stennis, Alabama (BSL), and Fredericksburg, Virginia (FRD).

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NORTH DAKOTA'S DAWN BEAR

BY JEFF J. PERSON

Finding something new to science can be an exciting thing; however, the one doing the finding typically doesn't know that what they've found is new to science, at least not at first. Often, the larger thrill of a discovery being unknown is elusive at first. These kinds of findings are not unique, but are rare enough to take note of when they happen. Although the NDGS joined the story of *Eoarctos* near its conclusion, these quests of understanding always seem to start simply enough. They usually start with the question, "What is that?" Three words, when put together can start you on a journey with an unknown conclusion. When first asked in 1982 on a plot of land in southwestern North Dakota, and then again in 2015 in an isolated room in the basement of the Heritage Center, this query sparked and re-sparked a flurry of research, answers, and even more questions.

In 1982 paleontologist Robert Emry was on an expedition for the Smithsonian Institution and was visiting a fossil locality in the southwestern corner of North Dakota. He had visited the area many times before and was hoping to collect more rock from a site he had found a few years earlier. The fossils from that site were numerous, tiny, and very well preserved. This same site was rediscovered by NDGS paleontologists 30 years later, and eventually named the "Coquina Locality" because of the sheer density of bones, jaws, and teeth found within. After collecting approximately 200 pounds of material from this first site in 1982, Dr. Emry began to search around the nearby area and discovered a few bones just beginning to erode out of the rock. He concluded that the bones were from a carnivore that he had never seen before and collected a large block of rock around the visible bones that he hoped contained the rest of the skeleton.

This fossil collected in 1982 is from the Brule Formation, which is approximately 32 million years old, dating back to what geologists call the Oligocene Epoch. More specifically, the Brule Formation rocks in North Dakota are from the boundary between the Orellan and Whitneyan ages within the Oligocene Epoch. In North Dakota, these rocks are found on the surface only in the southwestern corner of Stark and Slope counties. The environment during this time in North Dakota's history was similar to what you might find in the African Savannah today not only in flora, but fauna as well. The area was not wide-open plains, but a checkerboard of plains and forest with meandering rivers winding through the area. The animals on this ancient savannah consisted of rhinos, saber tooth cats, small three-toed horses, large pig-like animals, alligators, fish, and snails to name only a few of the known fauna.

FIGURE 1.
Left lower jaw of *Eoarctos vorax* NDGS 1593. (A) shows the occlusal and (B) the side view. Note the crenulations or wrinkles on the teeth. These crenulations add strength to the teeth, making them better for crushing hard shelled animals like snails. Drawings by Becky Barnes.

Fossils from the Brule Formation have been collected by the North Dakota Geological Survey for many years beginning in the late 1980s and early 1990s and continue to be collected to this day. The fossils from these collecting trips ended up in unsorted boxes and drawers during the early years of the North Dakota State Fossil Collection. As the fossil collection grew it became necessary to organize the fossils into collecting localities and then to separate animals within each locality. It was during one of these organizing periods that a very curious-looking lower jaw was discovered by Dr. Clint Boyd (curator of the ND State Fossil Collection) and me (fig. 1). This specimen had been picked up on a collecting trip in the 1990s and then placed in a drawer and forgotten about. The individual who picked up the fossil in the field likely did not have the expertise in the time period or in the group of animals to realize the magnitude of their discovery. This is not uncommon as North Dakota has a plethora of fossils from various time periods.

It would be nearly impossible for any one person to be an expert in all the time periods or animal groups collected from the breadth of localities across the state.

Research on the specimen quickly began to reveal the identity of the animal it came from. Vertebrate paleontologists use a variety of clues visible in the morphology (or shape) of an animal's teeth (especially in mammals) to place it in the overall "tree of life." Luckily, this lower jaw still retained nearly all the teeth, allowing identification of the larger group of mammals to which it belonged. Examination of the teeth revealed the animal belonged to the group of mammals called Carnivora, a specialized group that includes bears, dogs, cats, raccoons, skunks, weasels, and a few other smaller families. However, this animal did not fit neatly into any of these known families. Some of the tooth features were characteristic of bears, while others were characteristic of dogs, while still others were found within multiple other families of Carnivora. So where does it fit? How do we classify an animal that seems to be a chimera of features? After comparing this new jaw to others from the same approximate time period from other areas of the US, we decided it best matched the features of a group of animals called arctoids, which have a poor fossil record from this time period. It is within this group, just outside of the branch leading to modern bears, that this new creature should be placed (fig. 2).

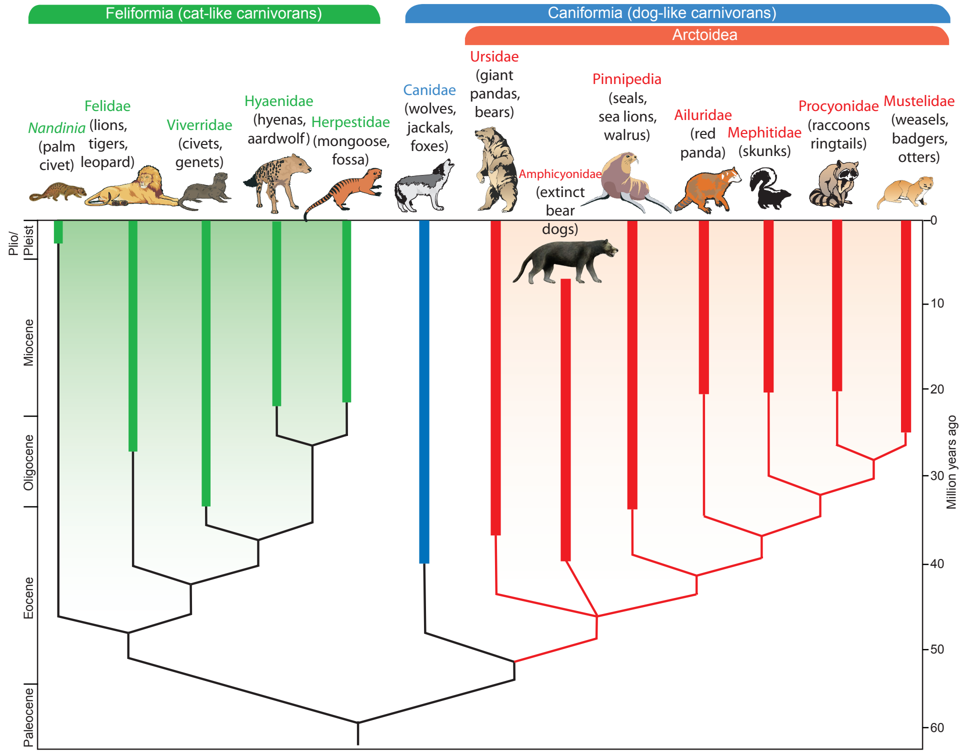

FIGURE 2.
Phylogenetic tree showing relationships of various groups of Carnivora. *Eoarctos vorax* belongs near the base of the thick red line defining Ursidae or bears.

This animal would have been about the size of a modern-day raccoon. Features of the teeth give us insight into the possible diet of this new critter (fig. 1). The teeth are slightly bulbous and low crowned, that is, they are short and squat. The teeth are also highly crenulated (wrinkled). Crenulations on teeth are often present in animals that have a need to crush hard items in their diet. Imagine this creature squatting alongside a slow-moving stream with a snail in its paws as it uses its crushing teeth to break the shell and then eats the raw escargot within (fig. 3). The name given to this new animal is *Eoarctos vorax*, which translates to "dawn bear the voracious eater."

The original lower jaw found in the NDGS collections was soon joined by additional specimens discovered during the next two field seasons. Since we didn't know what the rest of the skeleton looked like, every additional specimen we could confidently assign to this species consisted of lower jaws and isolated teeth.

FIGURE 3.
Eoarctos vorax feeding on snails near a North Dakota stream during the Oligocene Epoch approximately 32 million years ago. Painting by Mark Hallett.

FIGURE 4.
3D printed skeleton of *Eoarctos vorax*. The lighter tan portions of the skeleton represent pieces found in the original specimen. The darker gray portions represent pieces missing from the original specimen.

All the specimens we recovered were coming from the same small parcel of land in southwestern North Dakota. The same ranch, unknown to us, that Dr. Emry had recovered a specimen from, more than three decades earlier. That original specimen had returned with him to the Smithsonian Institution in Washington D.C. where the encasing rock had been removed revealing a nearly complete skeleton. Dr. Emry had also recognized that this specimen was a unique kind of Carnivora, but as he was not a specialist in this group of animals, he loaned the skeleton to the leading expert on early dogs; Dr. Xiaoming Wang, at the LA County Museum in Los Angeles, California, expecting Dr. Wang to take the lead on a full description and naming of this new animal.

During our research phase of the identification of this new animal, there comes a point where one needs to consult the input of other experts. It was at this stage that we reached out to Dr. Wang asking his opinion on where this animal would fit in the tree of life. Once Dr. Wang saw images of our specimen, he recognized the morphology immediately and realized we were working on the same animal that he was describing. We all decided it would work best for science to collaborate and publish information on the new species in one paper compiling all our specimens and giving a more complete picture of this newly discovered animal.

One large benefit of teaming up with Dr. Wang and his colleagues is access to the full skeleton of this new animal. The entire skeleton was 3D scanned during research and a copy of that data was offered to the NDGS for 3D printing and exhibition (fig. 4). The skeleton has been 3D printed and is now the newest addition to the geologic time gallery at the Heritage Center (fig. 5). A print of the commissioned mural by paleo artist Mark Hallett (fig. 3) is exhibited with the skeleton, compiling all the most recent information about the animal and environment *Eoarctos* inhabited in North Dakota 32 million years ago. To reflect the place in time when *Eoarctos* would have been living in North Dakota, special care has been taken to put the exhibit in proper sequence with existing exhibits. The new specimen is placed after the Paleocene swamp exhibit and adjacent to the current Oligocene exhibit. Come to the Heritage Center Geologic Time Gallery to see *Eoarctos*, the newest piece in the puzzle of prehistoric life in North Dakota.

FIGURE 5.
The new exhibit at the Heritage Center and State Museum in Bismarck featuring *Eoarctos vorax*. The 3D printed skeleton, lower jaw (NDGS 1593), as well as some terrestrial and aquatic snails can be seen in the exhibit case. Banner painting by Mark Hallett.

NEW PUBLICATIONS

All Survey publications (maps, posters, and reports) are available for free download from our website (www.dmr.nd.gov/ndgs/Publication_List/). Paper copies of 24K maps are $5, 100K are $10, and posters are typically $15.

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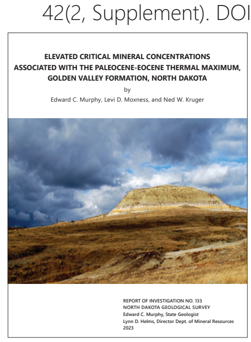

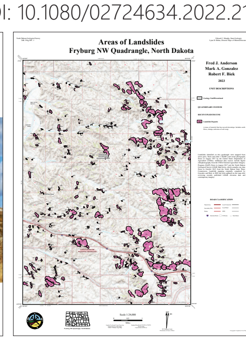

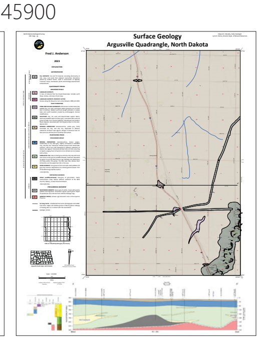

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