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ON THE COVER:
The orange-stained white rocks in the orange zone of the Bear Den Member of the Golden Valley Formation are well exposed along the west slopes of Harnisch Butte in Morton County. The thin carbonaceous beds (gray zone) beneath these brightly colored rocks contained elevated concentrations of rare earth elements. Tan-colored siltstone and mudstone (Camels Butte Member of the Golden Valley Formation) cap the butte. Photograph by Ed Murphy.

LYNN HELMS RETIRES

Led the Department of Mineral Resources for 19 Years

BY ED MURPHY

Lynn Helms retired on June 30, 2024, after serving as the Director of the North Dakota Department of Mineral Resources since its inception in 2005 when the Geological Survey and the Oil and Gas Division were merged into a new state agency. Prior to that, Lynn had served as the director of the North Dakota Oil and Gas Division since 1998.

Lynn Helms grew up on a cattle ranch near the Slim Buttes in northwestern South Dakota, roughly 30 miles from the North Dakota border. He earned a Bachelor of Science Degree in Engineering from the South Dakota School of Mines and Technology and later in his career a MS and PhD in Petroleum Engineering from the University of North Dakota. Lynn began his career as a petroleum engineer for Texaco for two years and then worked for Amerada Hess for 18 years as a production engineer, reservoir engineer and asset team leader across nine states, including North Dakota, as well as Abu Dhabi. His industry experiences proved valuable when regulating oil and gas companies and his early ranching experiences proved helpful when interacting with farmers and ranchers in western North Dakota and both experiences served him well when working with North Dakota legislators.

During Lynn's tenure with the State of North Dakota, producing oil wells rose from 3,155 to 18,734 as oil and gas production rose from 99,000 barrels per day to an all-time high of 1.5 million barrels per day in November 2019 before settling in around 1.2 million barrels. In addition to overseeing numerous changes to the state's oil and gas rules and regulations, the Class VI regulatory program was approved by the EPA for primacy in 2018. On the Geological Survey side, the subsurface mineral and geothermal rules were rewritten and new rules were created for in situ mineral mining. The Wilson M. Laird Core and Sample Library filled to capacity with cores and cuttings and a much needed $15 million expansion of the warehouse and laboratory facilities was completed in 2016. Also during Lynn's tenure, the Geological Survey led the nation in both the exploration for critical minerals in coal and the application of LiDAR to landslide identification and movement detection. The Paleontology Program grew significantly during Lynn's tenure. The Public Fossil Dig program expanded from one hundred available registration spots at only one location to over 600 spots at four locations across the state.

Lynn's wealth of oil and gas experience along with his quick wit enabled him to quickly dissect a problem and arrive at a solution. Though we wish him well in his retirement, Lynn's absence will be sorely felt at the Department of Mineral Resources, as well as throughout North Dakota state government and the state legislature for years to come.

REVIEW OF NON-BAKKEN/THREE FORKS

OIL AND GAS DRILLING ACTIVITY

In Western North Dakota Since 2013

BY TIMOTHY O. NESHEIM

INTRODUCTION

In 2023, the Bureau of Land Management (BLM) released a series of documents including one titled "Reasonably Foreseeable Development scenario for Oil and Gas Development" related to revising their regulations for BLM-managed acreage in North Dakota. While the BLM noted some of the historical diversity of oil and gas producing formations across western North Dakota, their forward outlook on projected activity nearly exclusively focused on the Bakken and Three Forks Formations, which have dominated the oil and gas landscape in the state for the past 15+ years. Specifically, the recently released BLM documents assumed the following through 2040: 1) exploration and development would nearly exclusively target the Bakken and Three Forks Formations, and 2) low development potential exists for acreage beyond a 5-mile buffer surrounding currently active/producing fields.

The BLM is probably correct in the assumption that developmental drilling activity in the state will be focused on the Bakken/Three Forks for many years to come. However, the assumption that exploration activity beyond the Bakken/Three Forks will essentially be negligible through 2040 may not be accurate. The Williston Basin of western North Dakota has yielded a variety of productive oil and gas plays and formations over the past 70+ years. To date, 18 oil and/or gas productive formations beyond the Bakken/Three Forks in North Dakota have combined to produce over 1.8 billion barrels of oil from more than 9,000 wells through the end of 2020 (NDOGD, 2023). This newsletter article reviews the activity in formations other than the Bakken/Three Forks during the past decade to highlight other opportunities beyond the Bakken.

REVIEW OF BAKKEN/THREE FORKS ACTIVITY

Since the beginning of 2007, just after the discovery of the Parshall Field which essentially launched North Dakota's Bakken oil boom, more than 18,000 Bakken/Three Forks wells have been drilled and completed (fig. 1). These wells have combined to produce more than five billion barrels of oil and nine trillion cubic feet of gas (NDOGD, 2024). Since the beginning of 2013, more than 12,000 Bakken/Three Forks horizontal wells have been drilled and completed, an average of more than 1,000 wells/year, which have combined to produce more than 3.3 billion barrels of oil and 7.3 trillion cubic feet of gas.

REVIEW OF NON-BAKKEN/THREE FORKS ACTIVITY (2013-23)

Overall, 335 wells have been drilled since the beginning of 2013 through the end of 2023 that were attempting to discover and develop oil and gas resources in formations other than the Bakken/Three Forks (figs. 1 and 2). Of those wells, 280 have been commercially productive to variable degrees and have combined to produce approximately 21 million barrels of oil and 25 billion cubic feet of gas. Of those wells, 56 were drilled vertically (including directional wells) and 224 were horizontal. Cumulative production from each well has varied from just a few barrels of oil to several hundreds of thousands of barrels. Additionally, 55 dry holes were drilled targeting non-Bakken/Three Forks reservoirs, consisting of wildcat wells in combination with unsuccessful developmental wells.

Of the 280 commercial oil and gas wells drilled in formations other than the Bakken/Three Forks during the past decade, some of those wells represented the continued development of established oil fields and reservoir/play types while other successful wells marked the discoveries of new fields and/or new play concepts in established, pre-existing fields. Below is an overview of the majority of those 280 wells.

Most of the wells drilled in southwestern North Dakota targeted the deeply buried Red River Formation (fig. 1). Activity in Bowman County was mostly comprised of developmental drilling of the Red River B laminated play, an open-hole horizontal play that was originally discovered in the mid-1990s with intermittent development thereafter (Montgomery, 1997; Diehl, 2001). Most of the continued development of the Red River B play was completed by Denbury Resources, who acquired the Cedar Hills South Unit in which the company recently initiated a CO_2 flood of the field for enhanced oil recovery. Further north, in Golden Valley County, Whiting Oil and Gas began to drill vertical wells using 3-D seismic to target localized porosity zones with the Red River C & D Intervals during the early 2010s (Nesheim, 2017a; Hill et al., 2018). Previously drilled wells in the area had targeted the Red River utilizing 2-D seismic. The transition from 2-D to 3-D seismic approximately doubled the success rate for drilling commercial Red River wells. Exploration and development in Golden Valley County continued into the mid-2010s but then dissipated with

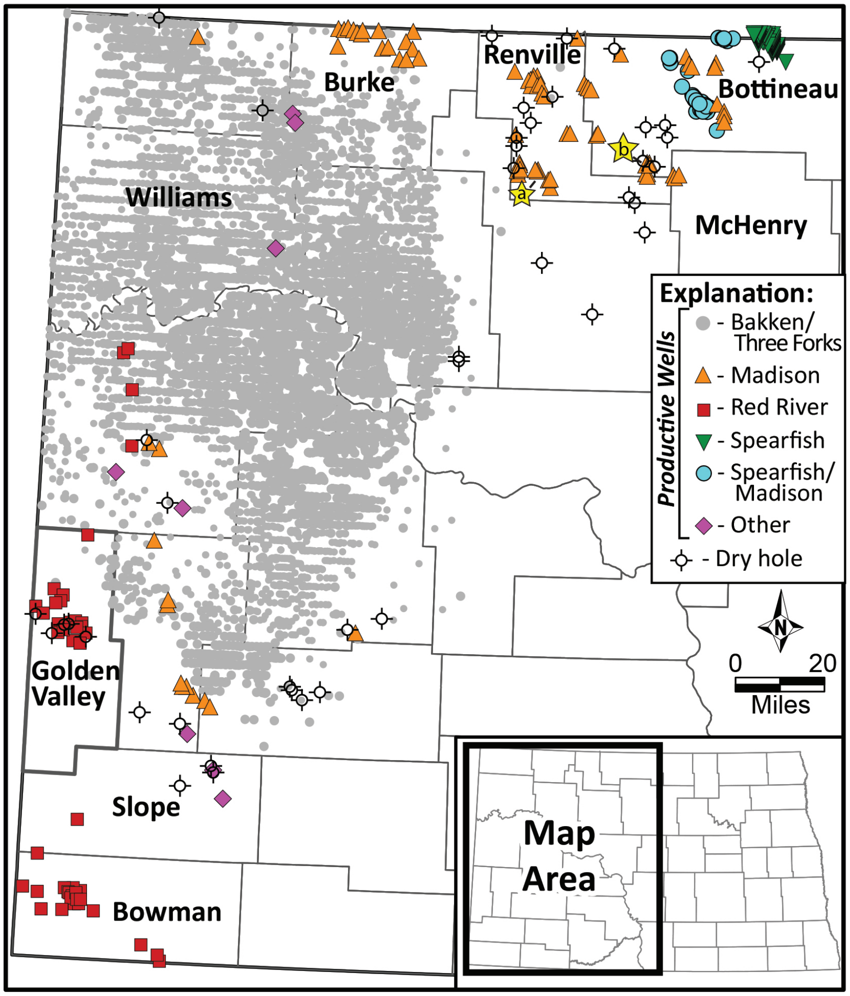

FIGURE 1.
Map of western North Dakota displaying all Bakken/Three Forks productive wells (includes every historical Bakken/Three Forks well) and non-Bakken/Three Forks wells drilled since 2013. County outlines are depicted as thin black lines and select counties are labeled. The yellow stars indicate recent Madison oil fields discovered: a) Feldner Coulee, and b) Chatfield. Most of the Spearfish/Madison wells indicated on the map (blue circles) were horizontal wells drilled within the basal Spearfish Formation.

decreased oil prices. Four new vertical Red River wells have been drilled in the area following the mid-2010s oil price drop, three of which have been commercially productive.

A substantial amount of the drilling activity in north-central North Dakota targeted reservoirs within the Madison Group, the second most productive oil and gas stratigraphic interval in North Dakota behind the Bakken/Three Forks. In 2014 and 2018, two conventional Madison oil fields were discovered in the southwestern corners of Renville and Bottineau counties, the Chatfield and Feldner Coulee Fields (fig. 1). Beyond that, most of the remaining Madison wells drilled in Renville, Bottineau, and McHenry Counties consisted of a combination of vertical and open-hole horizontal developmental drilling in pre-existing fields.

In northern Burke County, beginning in the mid-2010s, multiple operators began targeting low permeability carbonate reservoirs of the Midale and upper Rival subintervals of the Madison Group utilizing horizontal drilling coupled with hydraulic fracturing (Nesheim, 2019a; Starns and Nesheim, 2023). This play concept emerged within pre-existing oil fields and associated reservoirs that had previously been developed with vertical and open-hole horizontal wells. Drilling activity in this Midale-upper Rival play was relatively steady through early 2020, but then disappeared during the COVID-19 global pandemic when oil prices plummeted and have yet to pick back up.

Initiated by EOG Resources in 2010, multiple operators targeted the Spearfish Formation in north-central Bottineau County utilizing horizontal drilling coupled with hydraulic fracturing (LeFever, 2011; LeFever and LeFever, 2012; Stolldorf, 2019). This play led to the discovery of new Spearfish fields as well as the expansion of pre-existing fields. Sandstone reservoirs in the lower Spearfish section had previously been producing oil and gas through a combination of vertical and non-frac'd horizontal wells, but new technology renewed activity in the Spearfish for several years. The unconventional Spearfish play faded during the mid-2010s oil price drop and has yet to see a resumption in drilling activity.

Lastly of note, two unconventional projects were attempted with sub-economic results. The TI-WAO-157-95-14H-1 (NDIC: 26738, API: 33-105-03255) was drilled in the Tioga Field of southeastern Williams County (fig. 1) by Hess Corporation targeting the middle Lodgepole Formation (Nesheim, 2019b). The TI-WAO well was spudded in December 2013, completed in July 2014, and consists of a ~3,400-foot lateral that was completed with a multi-stage hydraulic fracture stimulation and has produced nearly 45,000 barrels of oil. Additionally, Marathon Oil Company drilled two horizontal wells targeting the upper Tyler Formation in northeastern Slope County during 2013-14 (fig. 1) (Nesheim, 2017b). Both wells included ~2-mile laterals completed with multi-stage hydraulic fracture stimulations that produced a few hundred to a few thousand barrels of oil before being plugged and abandoned. Each unconventional well was completed with fresh water, and the upper Tyler reservoir was found to contain fresh water-sensitive, swelling clays thought to have negatively interacted with the fresh water-based frac fluid.

DISCUSSION

Oil prices have played a key role in drilling activity during the past decade. In 2013 and 2014, when WTI pricing consistently averaged above $80/barrel, there were a total of 95 and 122 non-Bakken/Three Forks wells drilled in North Dakota (fig. 2). However, oil prices dropped in late 2014 through 2016, generally averaging around $40/barrel,

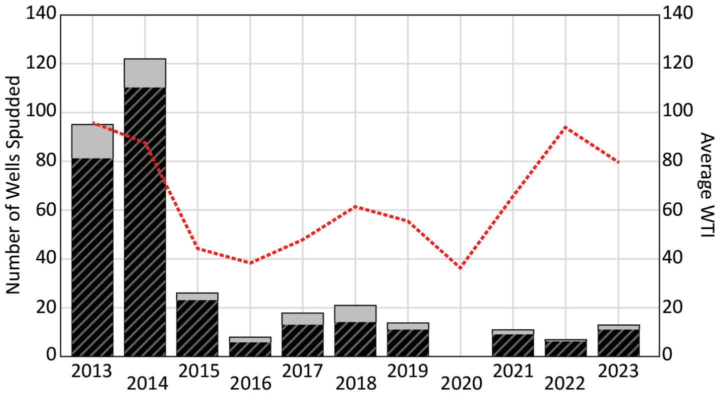

FIGURE 2.
Graph depicting the number of non-Bakken/Three Forks oil and gas wells drilled per year between 2013 and 2023 (productive wells in black and dry holes in gray), and the average annual WTI price of oil per barrel (red dotted line).

leading to a very pronounced decrease in drilling activity. Fewer than 30 non-Bakken/Three Forks wells were drilled in 2015 and <10 in 2016 (fig. 2). A slight rebound in pricing and drilling occurred during 2017-2018 but then declined due to the COVID-19 pandemic in 2020. While oil prices in the past few years have improved with some renewed non-Bakken/Three Forks drilling, activity has remained relatively low through the end of 2023.

The continued development of the Bakken/Three Forks play has very likely impeded the exploration and development of the other over and underlying hydrocarbon-bearing formations. The Bakken/Three Forks play spans more than 9,000 square miles (~6 million acres), a vast spatial footprint that encompasses dozens of legacy oil and gas fields that represents prospective acreage for exploration in many of the other units such as the Red River Formation and Madison Group reservoirs. Very few wells have been drilled within the core Bakken/Three Forks play area during the past decade which targeted other formations, likely because operators holding that acreage have focused on developing their established, low-risk, proved reserves in Bakken/Three Forks reservoirs (fig. 1). Overall, most wells drilled recently targeting other formations are located beyond the core development acreage of the Bakken/Three Forks play. Therefore, if not for the Bakken/Three Forks play emergence, activity in the other formations over the past decade would very likely have been more extensive across the western portions of the state.

The Williston Basin has historically been known for its diversity of stacked petroleum systems and hydrocarbon plays. In western North Dakota, 20 distinct formations have commercially produced hydrocarbons to date, including the Bakken and Three Forks Formations, which combine to span more than 400 million years of geologic history and over 10,000 feet of sedimentary section (Murphy et al., 2009). While the Bakken/Three Forks continues to dominate the oil and gas sector of western North Dakota, interest and activity in several of the other formations has persisted during the past decade. Eventually, activity in the Bakken/Three Forks play will dissipate as infill drilling continues to reduce the remaining well inventory in the prospective Bakken/Three Forks play acreage. This will likely lead operators to shift their collective focus beyond the Bakken and the diverse development opportunities that exist in other formations.

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Designing a CRITICAL MINERAL DRILLING PROGRAM

BY LEVI D. MOXNESS

Anyone who consumes U.S. or international news has likely noticed a steady uptrend in the number of articles relating to critical minerals over the last year or two. Seemingly weekly reports detail new assessments of conventional critical mineral deposits from researchers and exploration companies. At the same time, dozens of other research groups and laboratories explore the feasibility of tapping completely new sources and developing new extraction techniques to make them economic. This stream of headlines is the product of a wave of public and private capital investments into critical minerals a few years prior. The flows of news and funding are unlikely to slow down any time soon, as actual new production of critical mineral commodities has yet to materialize at a scale that can meet the anticipated global demand or reduce their efficacy as geopolitical chess pieces. The United States still relies on imports for all of its scandium and gallium, over 95% of its rare earth compounds and metals, and over 50% of its germanium, alongside dozens of others (USGS, 2024).

When will all these new discoveries across the globe see actual production? The vast majority likely never will, despite the exciting headlines. The jump from identifying an inferred mineral resource to realizing production is not a small one. A theoretical billion-dollar mineral deposit is effectively worthless if it costs $1,000,000,001 to explore, delineate, permit, mine, extract, and refine its ore. Uncertainty is one of the strongest barriers to capital investment into new mining, and there remains plenty of it in the critical mineral space. Which of these minerals will still be "critical" in five to ten years when a new mine would be operational? With demand for so many critical minerals driven by tech and energy applications, how can private industry forecast supply and demand in such rapidly evolving sectors? Can free market capital be effectively put towards critical mineral development if adversarial countries are willing to manipulate the global market to preserve their monopolies? If the U.S. and other Western countries are going to achieve critical mineral independence for their defense, technology, and energy industries, it may require some upfront investment before the private sector can take the reins.

The North Dakota Geological Survey (NDGS) was awarded $500,000 from the 68th Legislative Assembly to implement a critical mineral drilling program in the FY2023-2025

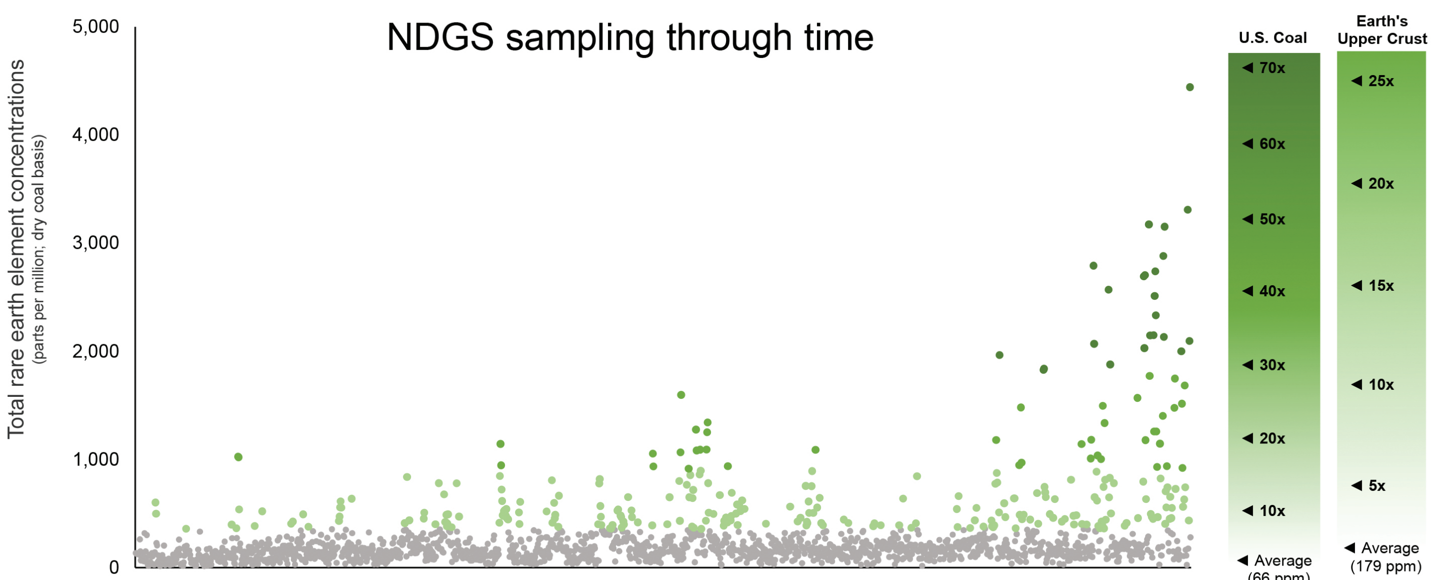

FIGURE 1.
Total rare earth element concentrations (including yttrium and scandium) for samples collected by the NDGS since the project began in 2015. The steadily climbing concentrations reflect the advances in our understanding of how and where enrichment occurs, allowing the project to evolve from random to targeted sampling. Average abundances of rare earths in U.S. coal and upper continental crust as determined by Finkelman (1993) and Taylor and McLennan (1985), respectively.

biennium as part of a joint project with the Earth and Environmental Research Center (EERC) at the University of North Dakota (UND). This 50-hole program will provide valuable subsurface information on the frequency of occurrence and extent of enrichment of critical minerals in two stratigraphic zones across southwestern and south-central ND. The significant enrichment in these zones was identified by the NDGS in part via previous support from the State legislature and North Dakota Lignite Research Council paralleling a separate effort by the UND College of Engineering and Mines to develop novel extraction techniques for critical minerals from lignite and mining by-products, which has received several rounds of funding from the U.S. Department of Energy for their promising results. This is in addition to federal support via the DOE's Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) Initiative awarded to the EERC. In short, there is a decade-long, bipartisan push at the federal level to turn critical mineral headlines in the U.S. into realized production, and there is broad support at the state level to make some of it happen here in North Dakota.

Regular readers of Geo News have received periodic updates on the NDGS effort to understand the distribution of rare earth elements and other critical minerals in North Dakota lignite. At the time of the first article examining these elements and the buzz that they could potentially be produced from coal (Kruger 2015), very little was known about the trace element content of North Dakota's estimated 1.3 trillion tons of lignite (Murphy et al., 2006), as only a few hundred analyses (often far less) had ever been reported for many critical elements (Palmer and others, 2015). Nine years, seven NDGS reports, and 1,830 analyses (fig. 1) from 325 sites later, we now know that not only is lignite in western North Dakota often enriched in multiple critical minerals, but we have a relatively cohesive understanding of how and where this enrichment occurs in perhaps the most important group of critical minerals, the rare earth elements. Two articles in last year's issues of Geo News go into more detail on these unique geologic settings: Quaternary weathering of long-lived upland surfaces (Moxness, 2023a) and intense Paleocene and Eocene weathering (Moxness, 2023b) enriching underlying lignite in rare earth elements up to fifty times the average concentrations of U.S. coal (Finkelman, 1993).

Enrichment at ten, twenty, or fifty times the average coal is on par with the highest reports in the nation and makes for good headlines, but it isn't worth much more than that if it is isolated or otherwise not recoverable. These unusually high rare earth concentrations appear constrained to lignites in two very narrow stratigraphic horizons: just below the Bear Den and Rhame bed paleosols. The two zones in which enriched coals can occur are each roughly 20 feet thick, representing very small intervals within the Williston Basin's 2,000+ feet of coal-bearing Paleocene and Eocene strata (fig. 2). So far, the thickest coals found in these intervals have been around two feet thick. Intervals of coal which are that thin could be economically targeted at existing mines (and at far lower concentrations utilizing preexisting mining infrastructure), but there are still many unknowns regarding the economics of pursuing thin hyper-enriched lignites as

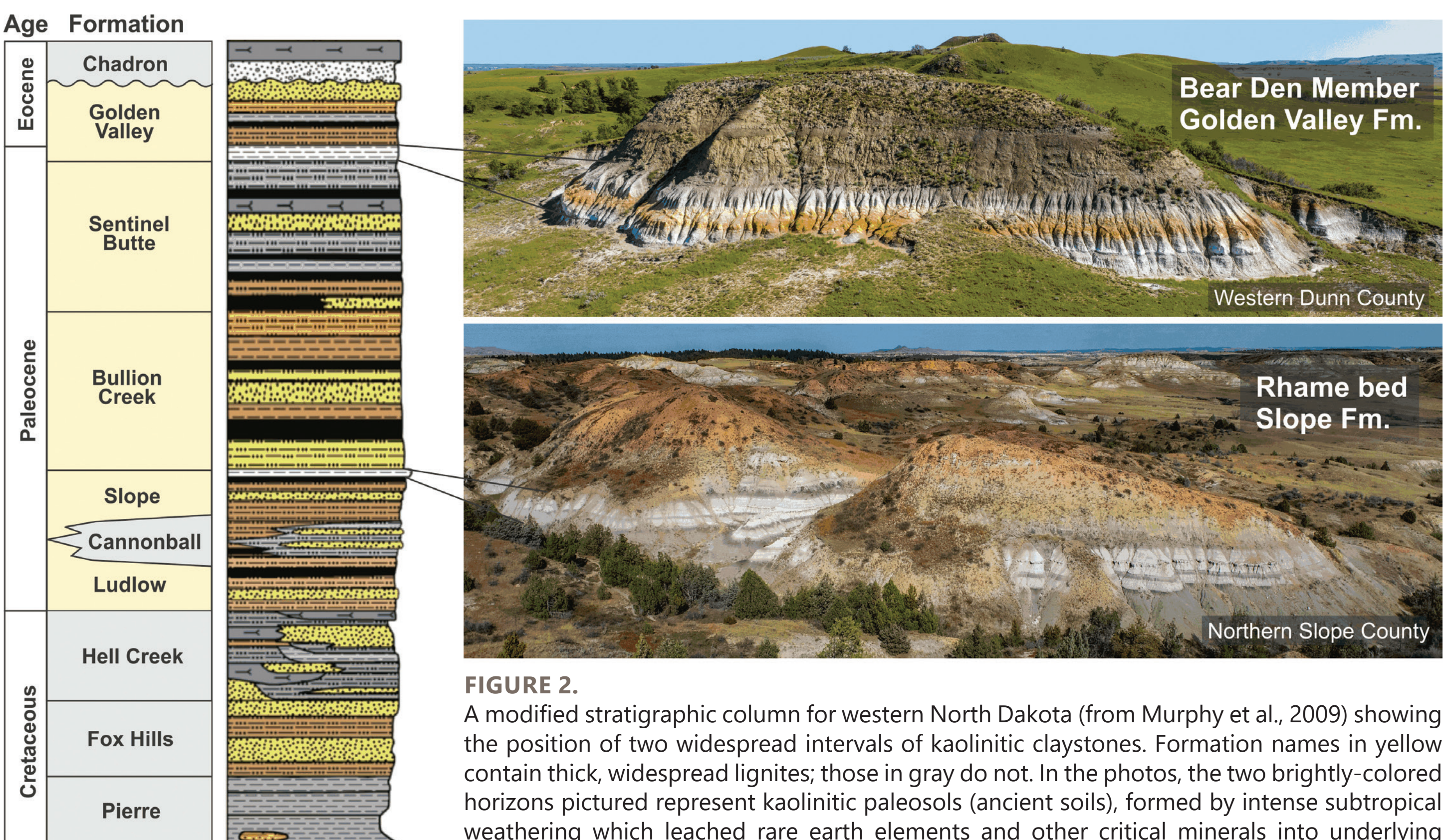

FIGURE 2.
A modified stratigraphic column for western North Dakota (from Murphy et al., 2009) showing the position of two widespread intervals of kaolinitic claystones. Formation names in yellow contain thick, widespread lignites; those in gray do not. In the photos, the two brightly-colored horizons pictured represent kaolinitic paleosols (ancient soils), formed by intense subtropical weathering which leached rare earth elements and other critical minerals into underlying lignites, where present.

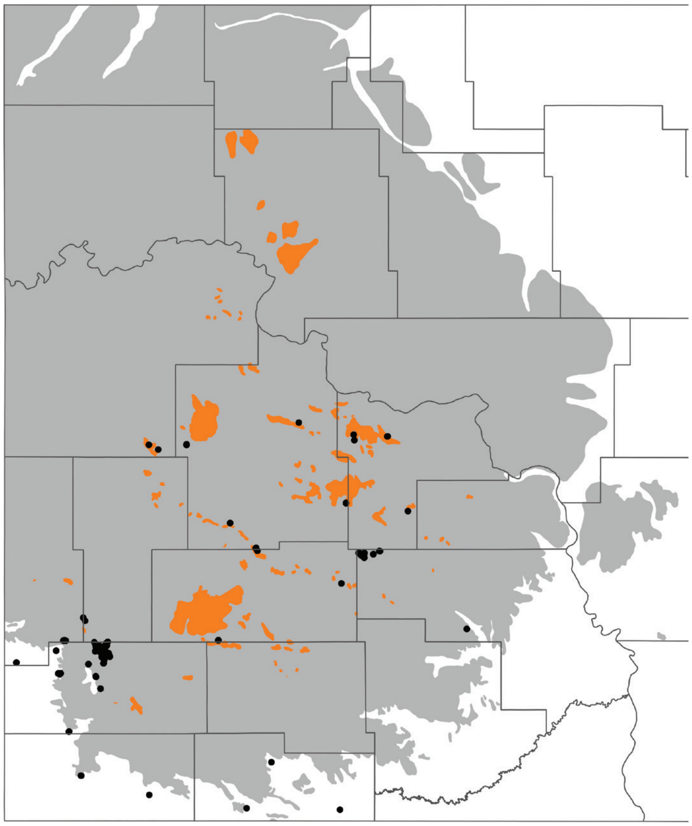

FIGURE 3.
The extent of the Bear Den Member and Rhame bed in the subsurface of western ND using mapping by Bluemle (1982). The Golden Valley Formation is mostly eroded away but significant areas remain scattered across the central portion of the basin. The top of the Rhame bed marks the contact with the overlying Bullion Creek Formation, which is still present over a much larger area but at a much greater average depth. Also, little is known about the strength of development of the Rhame bed in the middle and northern portions of the basin.

critical minerals ore. Some of the prospects will clarify in the near future as extraction technologies scale, but the most important characterization work to be done in the meantime is to determine the thickness, lateral extent, and degree of enrichment in these two promising zones.

There is reason to believe coals thicker than two feet are likely to exist within the target zones elsewhere in the basin but have not yet been documented. The NDGS has investigated only a few dozen sites within the vast area underlain by the Bear Den Member and Rhame bed (fig. 3). This is largely because the project to date has relied on accessible outcrops to collect surface samples. Good exposures are abundant in the Little Missouri badlands but are infrequent over much of west-central North Dakota and are even more rare northwards where they are overlain by younger bedrock or glacial sediments. After narrowing down the intervals of interest to just 2% of the overall thickness of coal-bearing strata, there is increasingly little that is left which can be reached by pickaxe and shovel. With the most informative outcrops already sampled, the only way to characterize these promising intervals is through drilling. But where?

The NDGS is fortunate to have access to a variety of data and tools to give us a better chance at finding and coring lignites, which are often thin or absent altogether in these tight stratigraphic windows. Geophysical logs from over 19,000 holes were interpreted and digitally cataloged in the late 1990s and early 2000s as part of the NDGS's study on the lignite resources of North Dakota (Murphy et al., 2006). These logs were collected by the coal, uranium, and clay industries, as well as test holes drilled by the North Dakota Department of Water Resources, coal exploration holes drilled by the NDGS and the United States Geological Survey, and oil wells with shallow gamma logs. The position of each interpreted coal can be plotted in three dimensions by using the digitized latitude, longitude, and depth subtracted from the listed surface elevation. New LiDAR elevations were also extracted for each given lat/long as a form of quality control, which identified wells with either imprecise elevations or misplaced locations.

The more difficult task is modeling the position of the Bear Den Member and Rhame bed relative to the coals in each hole. Driller's logs rarely note intervals of kaolinite or white claystone, likely because it is less obvious in drill cuttings, and attempting to identify them based on geophysical logs is a tenuous prospect. Fortunately, these bright white beds are (somewhat) easily traced on aerial imagery and elevations can be inferred remotely using high-resolution LiDAR data. Surficial mapping at the 1:24,000 scale has also been completed for most of the Golden Valley Formation, which was invaluable in informing the model. The value of having detailed-scale surface maps is especially illustrated in areas where some other unusually bright beds occur in the upper Sentinel Butte Formation (fig. 4), where extra care is needed so misplaced control points on similar-looking rocks do not locally throw off the modeled position of the Bear Den Member. Similar brightly colored horizons can also occur above the Rhame bed. After including the available mapping, a review of the aerial imagery, and additional field reconnaissance, three-dimensional models of both weathering zones were created based on 314 control points for the Rhame bed and 394 for the Bear Den Member.

Although most of the geophysical logs overlap with the theoretical extent of the Rhame bed (i.e., most of the Williston basin) the spatial extent of the model can be limited to reasonable depths. Carlson (1985) tentatively identified a zone of high resistivity at a depth of 1,214 feet as the Rhame bed in northern McKenzie County. As interesting as it would be to investigate the Rhame bed near the center of the basin, the NDGS decided to focus on lignites at less than 150 feet in depth. This will not only keep the costs of the drilling program lower, but it is roughly in line with the limits of conventional surface mining. This restricts the potential area of the Rhame bed to the southeastern margin of the basin (fig. 5) since it is generally buried by several hundred feet of glacial sediments to the north (Bluemle, 1982), assuming

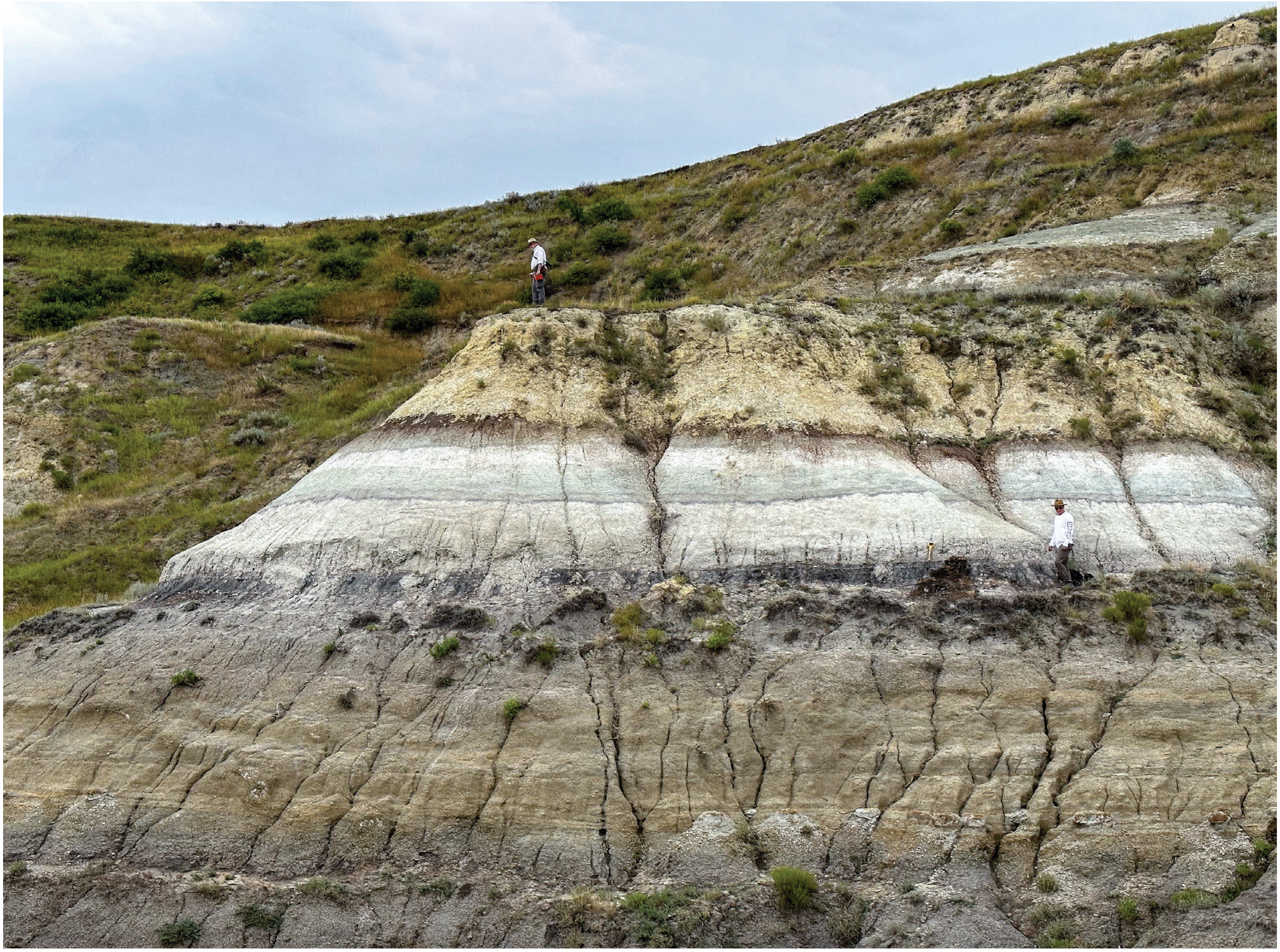

FIGURE 4.
A bright colored mudstone in the upper Sentinel Butte Formation, in Northern Billings County. Localized bright beds like this one can cause confusion when mapping the Rhame bed and Bear Den paleosols, especially from aerial imagery. Although similar in color and thickness to the other two paleosols, this bed did not leach rare earths elements into the underlying coals.

it even developed on that side of the basin in the first place. The Bear Den Member is typically much shallower, but it too is overlain in places by several hundred feet of Eocene, Oligocene, and Miocene bedrock, or glacial till along Lake Sakakawea and northwards.

With the position of both target zones estimated and populated within the geophysical logs via Petra software, the cataloged and interpreted logs can be filtered to those with 1) coals, 2) at practical depths (under 100 feet), and 3) coals within an interval 20 feet above and 50 feet below the modeled top of the Bear Den and Rhame bed paleosols. The latter interval was intentionally set wider than the anticipated 20-foot-thick zone of enrichment to include a vertical margin of error for both the well logs and the model. These filters reduced the number of wells that could be manually inspected from 19,655 to just a few hundred each for the Rhame bed and Bear Den Member.

The final step was to pick specific parcels for drilling permission within areas that appear to have thick coals in the right stratigraphic position at shallow depths. The NDGS has worked with interested private landowners throughout the project, but most of the sampling work to date has been on U.S. Forest Service or ND State Trust Lands, with whom the NDGS maintains collection permits. Working off permits with public agencies that cover dozens of parcels can save considerable time upfront, and outside of a few preexisting landowner contacts in Morton and Slope counties, it was elected to continue to leverage these public partnerships for the drilling program, if possible. Federal lands are mostly limited to the Little Missouri badlands on the far west side of the state, which has already been well-sampled without drilling. The North Dakota Department of Trust Lands, by contrast, manages significant acreages with mineral rights retained by the State across west-central ND, providing excellent overlap with the areas of interest.

Focusing drilling on State-owned mineral lands also meets the Survey's responsibilities as outlined in the North Dakota Century Code Section 54-17.4-02: 13. *Investigate the kind, amount, and availability of the various mineral substances contained in state-owned lands, so as to contribute to*

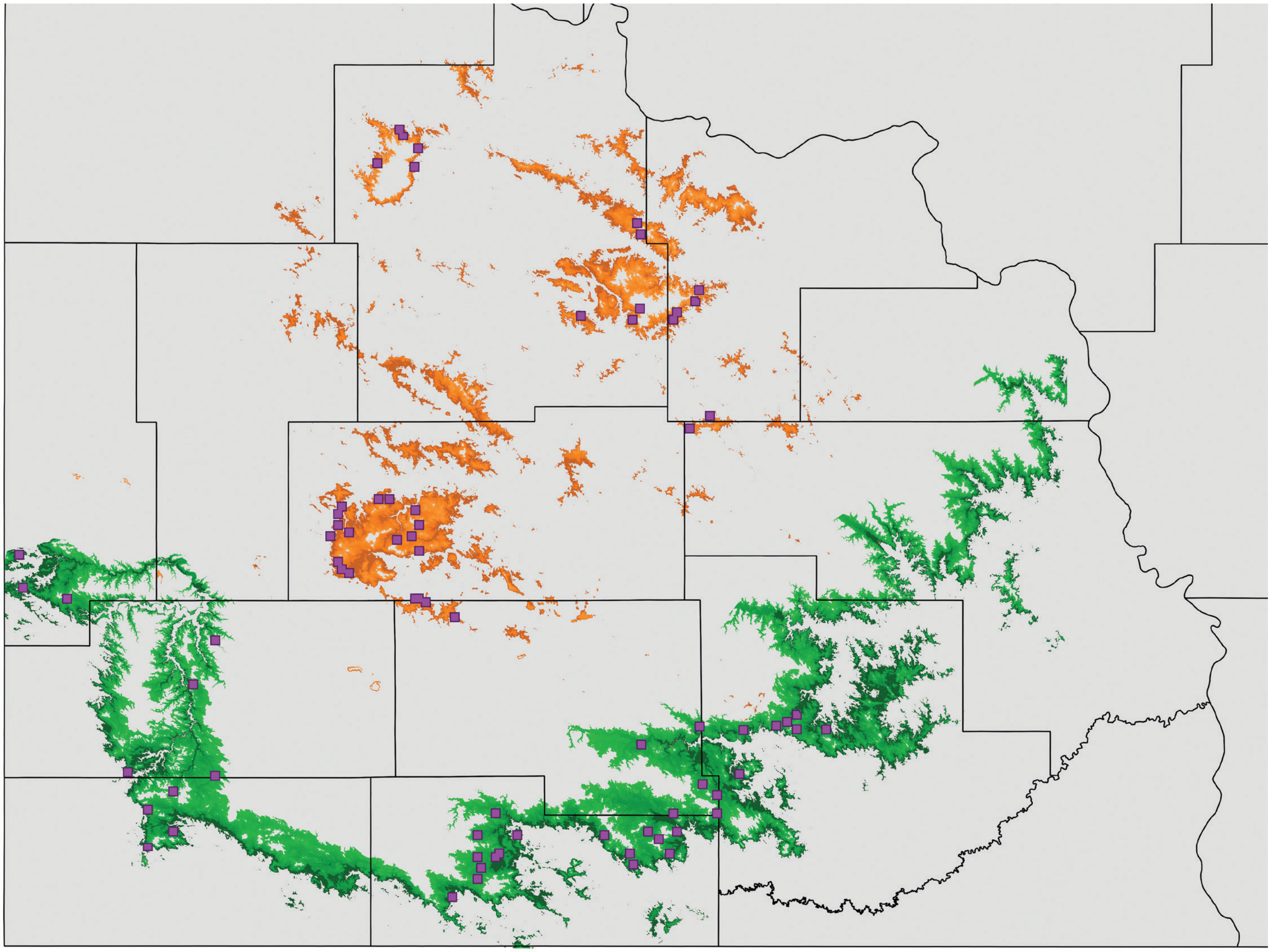

FIGURE 5.
Modeled positions of the Bear Den (dark orange) and Rhame bed (dark green) paleosols and areas where the upper contact is within 100 feet of the surface (lighter orange and green, respectively). ND State Trust mineral tracts permitted for drilling by the NDGS in 2024 are represented by purple squares.

the most effective and beneficial administration of these lands for the state. After discussions with the ND Department of Trust Lands on the scope of the project and the optimal number of tracts that would provide the drilling program a degree of flexibility, the NDGS submitted a permit request for 75 tracts, which was approved in March 2024. Drilling is set to take place in late summer of 2024, so readers of Geo News can expect updates in forthcoming issues on results from the program and what they mean for the extent of enrichment of critical minerals in these unique lignites in western North Dakota.

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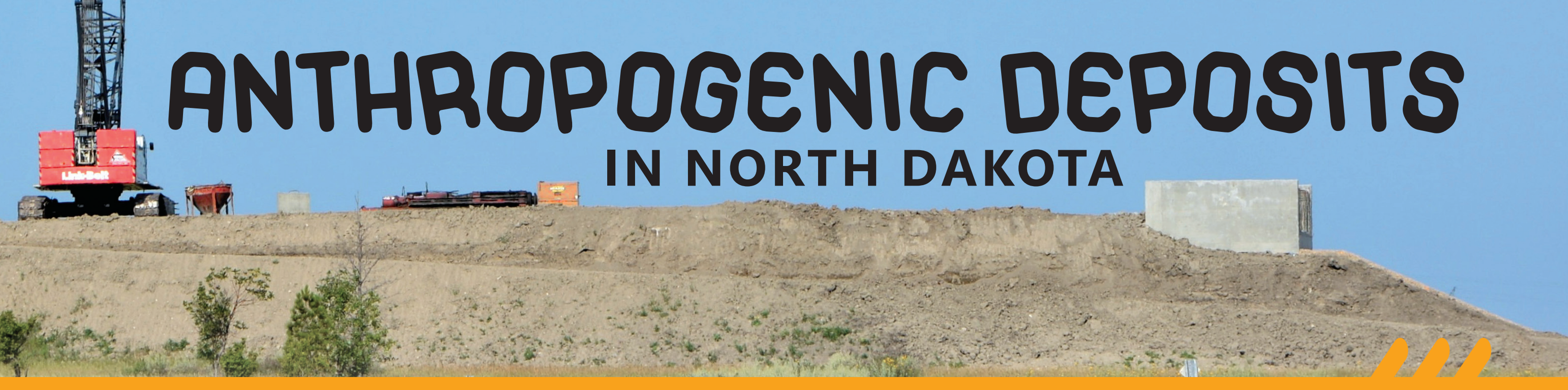


ANTHROPOGENIC DEPOSITS
IN NORTH DAKOTA

BY FRED J. ANDERSON

Anthropogenic is a relatively new term now being used to describe geologic deposits placed by humans using artificial methods, most commonly in North Dakota during construction activities. Placement of fill for large construction projects such as bridges, highway interchanges, large buildings, and well pads will all contain deposits that have been modified. In most cases properly so, by human activity (fig. 1). Sometimes this material can also be called "engineered fill" if it has been designed with certain performance specifications in mind. Knowing where these materials occur and have been placed can be helpful when issues arise from poorly selected excavations or improperly placed fills, those that were not properly engineered in the natural landscape. The NDGS first started recognizing artificial deposits on geologic maps at locations of solid waste landfill facilities or where wastewater ponds were constructed in the 1980s.

FIGURE 1.
Reconstruction of an overpass on I-29 south of Fargo is an example of a type of anthropogenic deposit that can be included on modern geologic maps completed in the urban environment.

Today, it is not uncommon to see the symbol Af at the top of a legend on a geologic map, where the lowercase f stands for "fill" and the uppercase A stands for "Anthropocene," the geologic period where humans have been able to modify their natural environment. The term anthropogenic is also sometimes used. The Af symbol and description will most commonly be found at the top since the description of deposits found on a geologic map commonly follows the convention of the description of the youngest materials at the top and the descriptions of progressively older deposits towards the bottom.

Anthropogenic deposits occur widely across the urban geologic environment. Filling drainage swales or old ponds and sloughs with improperly placed backfill can result in poor foundation conditions for residential and commercial property development. For example, if drainage swales or ponds and sloughs are simply bulldozed over during land development, they may continue to cause damage to infrastructure, residential, and commercial properties well

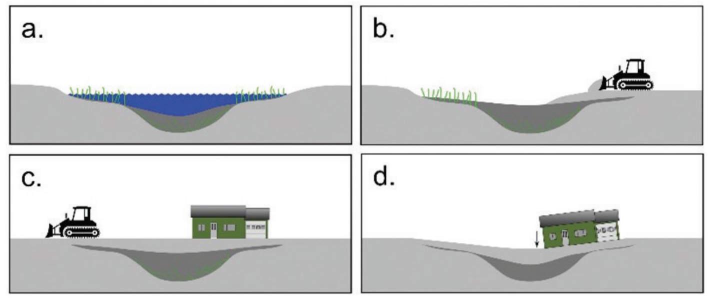


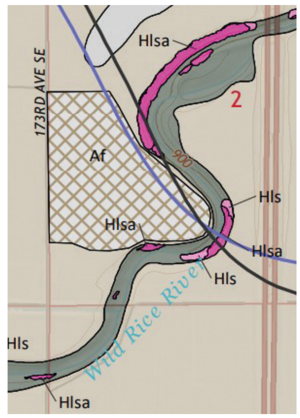
FIGURE 2.
Former drainage area before residential development (a), filling in old drainage area before residential development (b), construction above filled area (c), subsidence of structures over time as filled area dewaters and compacts (d).

into the future. These areas likely contained weak, water-saturated organic soils and may continue to provide for shallow groundwater and stormwater conveyance if not properly accounted for during construction (fig. 2).

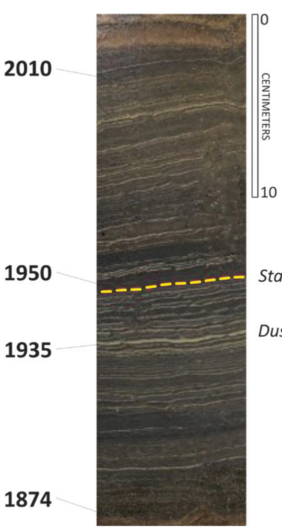
Taking an example from one of our recent geologic maps of the greater Fargo area, we mapped the locations of fill deposits that were placed as part of the new flood control structures being constructed around Fargo (figs. 3 and 4). We also mapped where new fills were being placed for bridge and interchange construction and where fill deposits had been placed along newly excavated drainage improvements across farm fields. Years from now, as development continues to expand into these areas, having geologic maps and aerial imagery that note where these deposits were can help to assist geologists and engineers when addressing future forensic geotechnical challenges.

It seems reasonable to define the Anthropocene as that period where humans have influenced their geologic environment. However, it is much more difficult to decide just where to mark this point in time as there are many things to consider. From the perspective of geologic time, scientists from around the world, who are part of the Anthropocene Working Group, have proposed a formal definition and stratigraphic marker for the beginning of the Anthropocene at 1950 since this is the year that nuclear bomb testing scattered plutonium into the atmosphere and is detectable worldwide (Spencer, 2022). A lake deposit at Crawford Lake, Ontario, Canada (fig. 5) has been proposed as a candidate site, along with several others, that would define this new stratigraphic boundary. This site was chosen since the annual layered lake sediments can be dated very

↑FIGURE 3.
Bulldozer reworking offshore glaciolacustrine deposits of the Sherack Formation south of Horace during the summer of 2023. Seen in this photograph is the plastic nature of the clays within the Sherack Formation creating large blocks of clay and silt which will eventually be recontoured and recompacted into a broad wide flow channel leading into one of the Fargo Diversion control structures. The municipal water tower for the City of Horace can be seen in the background at left. The view is to the north.



↑FIGURE 4.
Excerpt from a geologic map of an area mapped as containing anthropogenic deposits (Af) where construction activities on the Fargo Diversion were completed.



←FIGURE 5.
Section of the uppermost portion of lacustrine core from Crawford Lake, Ontario. Like pages in a book, each layer can be precisely dated and correlated to natural and anthropogenic events in North America. Additional dates, 1874 and 2010, are included for reference (modified from Chagas, 2023).

accurately (Zhong, 2023) and contain the radiological markers and geochemical components that are evidence of human activity influencing the geologic environment.

The U.S. Geologic Survey currently does not recognize the Anthropocene as a formal geologic name (Orndorff and others, 2022). Nevertheless, at the NDGS we continue to refer to the Anthropocene as the period in which humans have altered their geologic environment and delineate anthropogenic deposits on our geologic maps as those commonly related to infrastructure and construction activities. From the perspective of geologic time, we are currently living in the Meghalayan Age of the Holocene Epoch (AWG, 2022) but this would change to the Anthropocene if it does become fully recognized by the geologic community (fig. 6).

At the time of this writing, geologists from the International Subcommission on Quaternary Stratigraphy (SQS) voted against the proposal to formally make the Anthropocene a recognized geological epoch. This vote was not unanimously approved and is being challenged by other members of the committee on procedural grounds (Witze, 2024). Whether or not the Anthropocene eventually becomes recognized as a formal segment of geologic time, the practice of delineating geologic deposits placed by human means will remain an informative and practical aspect of modern-day geologic mapping in the urban environment.

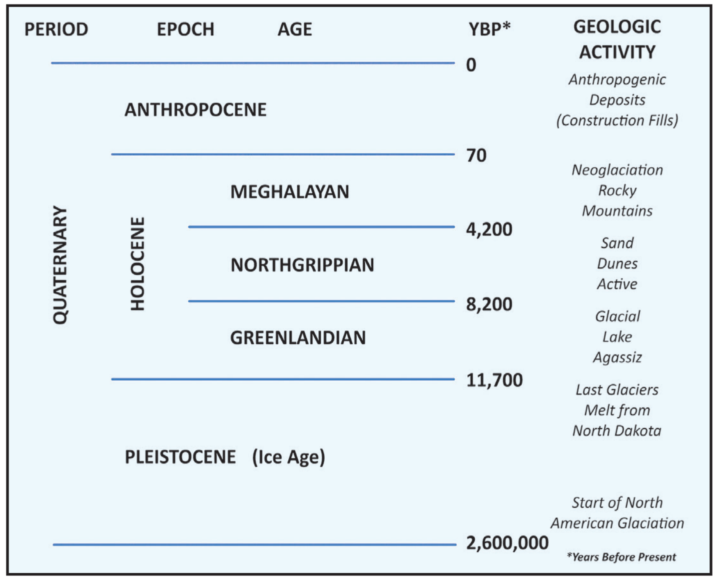


FIGURE 6.
Quaternary time scale highlighting the ages of the Holocene and geologic events in North Dakota and the region (modified from Bluemle, 2000; AWG, 2022). This shows the Anthropocene as a distinct geologic epoch that would terminate the Holocene in the middle twentieth century.

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PROMOTING GEOTHERMAL HEAT PUMPS

BY NED W. KRUGER

Geothermal heat pumps, also known as ground-source heat pumps or geoexchange systems, move heat from one area to another, much like a water pump can move water uphill. During cold months, a refrigerant is moved through a series of closed loops placed below the frost line, absorbing heat from the ground, which is then brought into a heat-exchanging unit to warm the building, or the process can be reversed to cool the building by removing its heat and placing it in the ground during the summer. The technology takes advantage of two primary principles of heat transfer, 1) areas of higher temperature will flow to areas of lower temperature and 2) the rate of heat transfer is proportional to the difference in temperature between the two areas. In North Dakota, the shallow ground temperature remains around 45 degrees Fahrenheit (7 degrees Celsius) throughout the year, contrasting nicely with summer high and winter low outside air temperatures.

Though geoexchange system-use history in North Dakota predates it, the state's geothermal program began in 1984 at which time a permit became required for all commercial installations. Permits became a requirement for residential systems beginning in 2007, though some installations before that time had voluntarily applied and were therefore captured in our database. Through the end of 2023, a total of 1,843 permits have been issued (fig. 1), accounting for 40,685 vertical loops and over 8.4 million feet of boring length drilled. Figure 2 depicts the distribution of these permit locations by county.

One of many roles of the North Dakota Geological Survey is to promote and encourage the proper use of geothermal resources in a manner which will prevent waste. This is done, in part, by informing the public of the advantages geothermal heat pumps offer; advantages such as significant energy cost savings, quiet operations, low maintenance, even heat distribution, year-round humidity control, the lack of carbon monoxide fumes and fire risk, hidden outdoor infrastructure, and the ability to reduce even your hot water costs. Those are a lot of advantages on a personal level, without even touching upon the environmental advantages. These advantages are offset by the initial higher cost to install the systems, which can be several times higher than other more conventional heating and cooling systems. While future energy savings can generally recoup this capital investment over a period of years, it remains an obstacle for consumers who would be otherwise interested in geothermal technology.

A lull in commercial and residential geothermal system installations in North Dakota is dragging on for the ninth year. A total of 27 geothermal permits were issued in 2023, far off from the all-time highs of 235 and 245 permits in 2010 and 2011. On a positive note, however, it was the most activity in the past six years (fig. 3).

A previous issue of Geo News (Manz, 2018) explained how, along with the low cost of natural gas, the loss of two major tax rebate programs likely contributed to the reduction of permit applications in subsequent years. First, a state renewable energy tax credit covering 15% of geothermal system installation costs expired at the end of 2014. Two years later a federal tax credit of 30% of these costs also expired combining for a loss of 45% in installation cost recovery previously

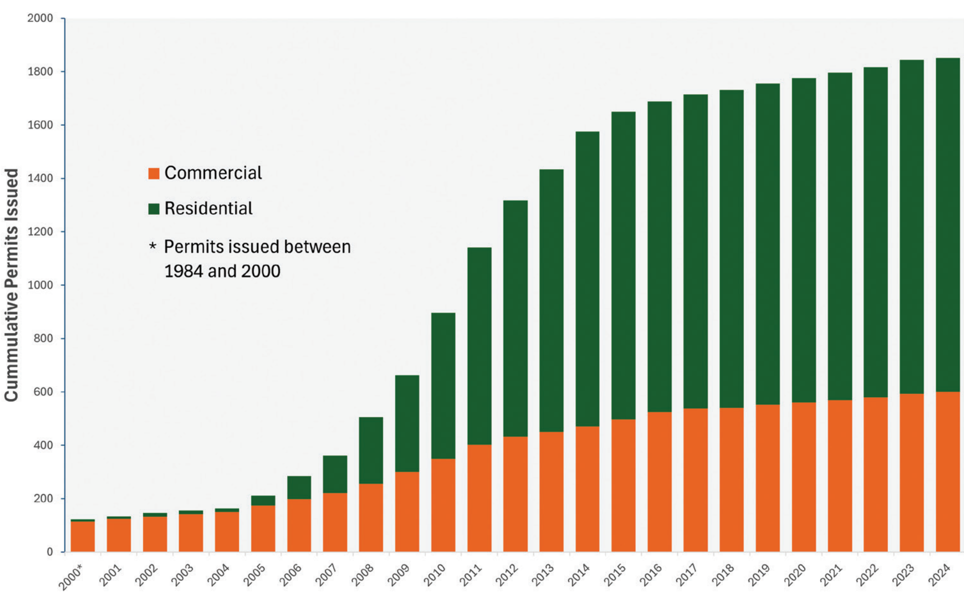

FIGURE 1.
Annual cumulative totals of geothermal installations in North Dakota.

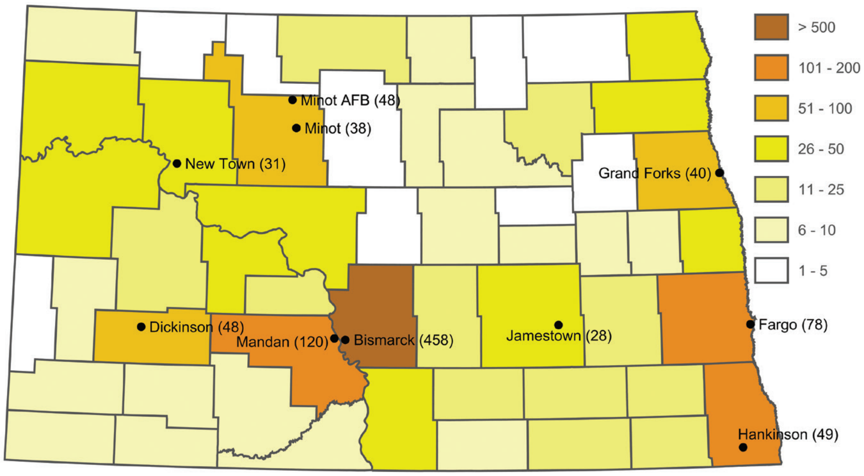

FIGURE 2.
Distribution of geothermal systems by county. Communities with a minimum of 25 installations are identified with the number of installations shown in parentheses. Off-base installations are included in the figure for Minot Air Force Base. The cities of Williston and Hillsboro just missed the cutoff with 24 and 23 systems, respectively. There is now at least one geothermal heat pump system in every county of the state.

available. Geothermal heat pumps were once again made eligible for the Residential Clean Energy Credit in 2018 and the law currently allows credit for 30% of installation costs through 2032, then phases down to 26% in 2033 and 22% in 2034 (IRS, 2024).

According to the U.S. Environmental Protection Agency (EPA), geothermal heat pumps are the most energy-efficient, environmentally clean, and cost-effective systems for heating and cooling buildings. Modeling analyses by Oak Ridge National Laboratory and the National Renewable Energy Laboratory have found that the use of geothermal heat pumps in 70% of U.S. buildings, along with structural heat loss improvements, could save about 15% of our country's current electric demand (NREL, 2024). They further estimate this could save 24,500 miles of new grid transmission lines over coming decades from a reduced need for capacity, storage, and transmission of other types of energy production. Geoexchange systems also lessen the load demands on electricity producers at peak times during extreme hot and cold weather events, reducing the likelihood of blackouts or brownouts.

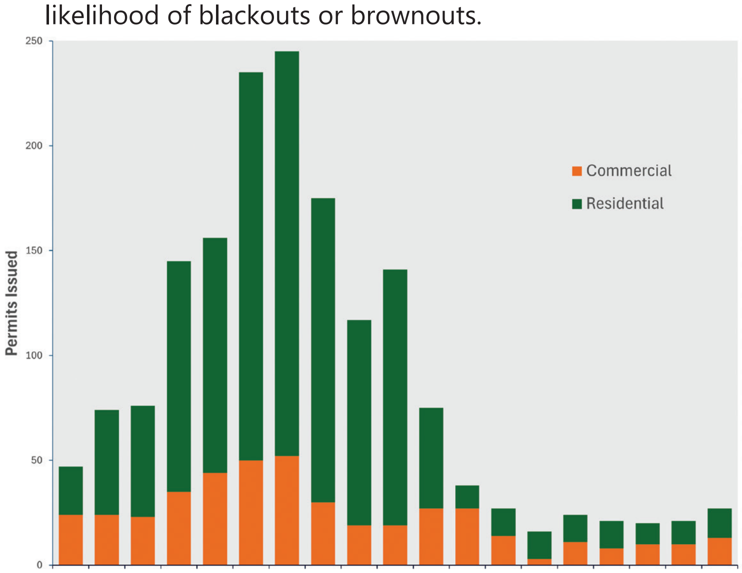

FIGURE 3.
Permits issued from 2005 through 2023. While residential systems were exempt prior to 2007, residential applications began to be voluntarily filed more regularly in 2005.

Examples like this show that there can be a societal benefit to greater levels of geoexchange system usage, even to those who aren't directly using them. If federal and state governments are going to promote renewable energy products, it makes sense that geothermal should be a preferred method to heat and cool buildings.

So, what can be done to make geothermal exchange systems a better option for average and lower-income American families? Geoexchange®, an advocacy organization for the geothermal industry, is promoting the merits of third-party ownership for geothermal systems and asking federal policymakers for tax guidance and clarifying language in support of leasing options (Geoexchange®, 2022). In a nutshell, a commercial third party would pay for the construction of a geothermal exchange system and lease it or sell energy to the consumer, be it a homeowner, renter, or business. The consumer would immediately receive cost savings in their energy bills without needing to lay out the capital investment to build the system. The third-party ownerships are better positioned to reduce the cost of the system by taking advantage of lower commercial interest rates, accelerated depreciation, and tax credits. Other renewable energy technologies have already experienced growth based on similar leasing models.

There are some questions about how this would work with a third-party ownership of a geothermal system inside your own house compared to, for example, wind turbines located not in your home but elsewhere on your land. Still, stakeholders are busy trying to figure it out. Perhaps it will help nudge the next upswing in geothermal activity in North Dakota.

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In The *SHADOWS* Of DINOSAURS

BY JEFF J. PERSON

Scurrying through the underbrush, scampering up a fallen log, the small mammal races from shadow to shadow trying to remain hidden from the prying eyes of the small carnivorous dinosaur. While this small creature may act and look like a rodent, and eat the same foods as rodents, it is not a rodent at all. In fact, our modern classification system barely classifies it as a mammal (fig. 1). This group of animals, evading the watchful eyes of predatory dinosaurs, are called multituberculates, sometimes considered the rodents before rodents. So named due to the many, many cusps on their molars (fig. 2), the multituberculates first appeared in the Kimmeridgian (Late Jurassic, 150 mya) and survived until the late Chadronian (Paleogene, 35 mya) making them one of the longest-living orders of mammals (Weil & Krause, 2008). Most genera of multituberculates were relatively small, approximately the size of a modern mouse, but one called *Taeniolabis*, found in nearby Montana and Saskatchewan, reached the size of a modern beaver (Weil and Krause, 2008). Since North Dakota was covered by an inland sea for most of its history, the fossil record of multituberculates in North Dakota does not begin until the Late Cretaceous approximately 65-67 mya (Boyd et al., 2017). Four genera of multituberculates coexisted in North Dakota during this time: *Essonodon, Mesodma, Cimolodon, and Meniscoessus*. For many years the focus of fossil recovery during this time in Earth's history was on the larger dinosaurs. Only in the last few decades has the focus started to shift to the recovery of the smaller animals. Due to the size of these animals, recovering their fossils can be difficult so it is likely that this Late Cretaceous record is incomplete.

After the extinction of the dinosaurs (66 mya), multituberculates continued to thrive in North Dakota. At least six genera of multituberculates have been recovered from Paleocene rocks in North Dakota (*Ptilodus, Prochetodon, Mesodma, Ectypodus, Neoplagiaulax, and Parectypodus*) (Kihm and Hartman, 2004), and a seventh Paleocene genus (*Taeniolabus*) recovered in nearby eastern Montana (Simmons, 1987). By Eocene time (55 mya) only two genera (*Parectypodus* and *Ectypodus*) remained in North Dakota or anywhere else in the United States. So, what happened to the multituberculates? Why the sudden and drastic decline in genera at the end of the Paleocene?

A few explanations for their extinction have been proposed, but none fit the sparse evidence perfectly. Were the multituberculates forced out of their ecological niches by animals better adapted to fill those niches? Rodents, as we know them today, first appeared during the late Paleocene approximately 58 million years ago, roughly eight million years after the extinction of the dinosaurs. A few million years after that, rabbits and other modern orders of mammals first appeared during the Eocene. These orders of mammals (mostly Rodentia and Lagomorpha, rodents and rabbits respectively) have proven, over the last 50 million years or so, to be very successful in their respective roles in the biosphere. It is possible that these two orders were simply better at surviving and reproducing in these environments than the now extinct multituberculates. The problem with this hypothesis is that multituberculates coexisted with both groups for millions of years before finally going extinct. Something that should have taken no more than 1 or 2

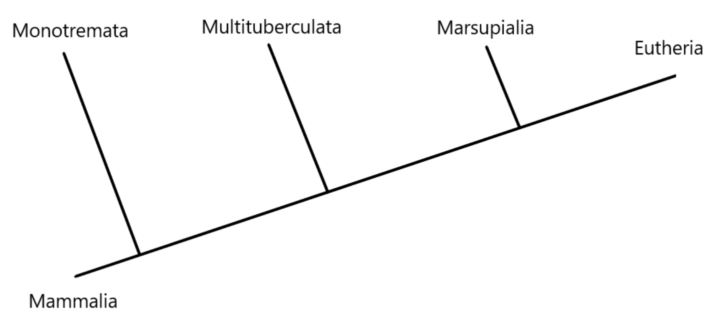

FIGURE 1.
Generalized family tree of mammals. Monotremes are egg-laying mammals (e.g. duck-billed platypus and echidna). Multituberculates are the extinct group of mammals with numerous cusps or bumps on the surface of their teeth. Marsupials are pouched mammals (e.g. kangaroo and opossum). Eutherians are the “true” mammals (e.g. humans, horses, etc.).

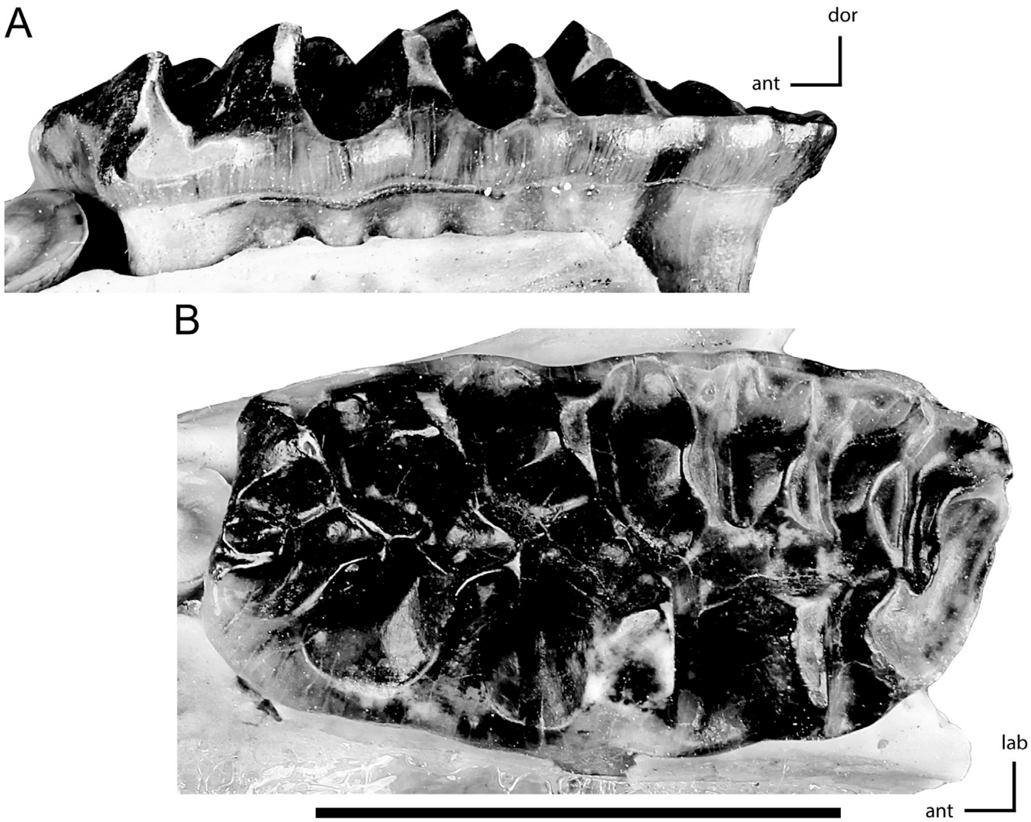

FIGURE 2. Labial (A) and occlusal (B) views of the multituberculate *Essonodon browni* (NDGS 1792) from the Late Cretaceous (Lancian) Hell Creek Formation of southwestern North Dakota. Note the numerous ridges or cusps along the surface. Abbreviations: ant, anterior; dor, dorsal; lab, labial. The scale bar equals 5mm. Modified from Boyd et al., 2017.

million years took 20-25 million years. If rodents and rabbits were so much better at surviving, why did it take so long for the multituberculates to go extinct?

Fifty-five million years ago, at the boundary between the Paleocene and Eocene geologic epochs, there was a global rise in temperature large enough to severely affect marine life across the globe. Referred to as the Paleocene Eocene Thermal Maximum (PETM) it was a time of sudden biological turnover in both marine and terrestrial faunas. It was during the end of the Paleocene that multituberculates declined in both variety and population. However, a link between multituberculate extinction and the change in climate during this time was debunked by Krause (1986). While climate change can be detrimental to creatures, there is no apparent link between the rise and fall of multituberculate populations and climate fluctuations in the Paleogene.

Krause (1986) also discussed the hypothesis of multituberculate extinction being linked to populations of mammalian and avian carnivores. While the idea of an animal being hunted to extinction by one or more groups is certainly not hard to imagine, the problem with this idea is the lack of evidence in the fossil record. Carnivores are high on the food chain and therefore have smaller populations. Trying to associate fluctuations in carnivore populations with the rise or decline in multituberculate populations is impossible in the fossil record due to the very nature of the fossil record being incomplete. We have no way of knowing how accurately the proportions of collected fossils reflect the actual proportions of ancient faunas.

In North Dakota, we have a record of multituberculates from the Lancian (Late Cretaceous), until their ultimate demise in the Chadronian (Paleogene). On a small, unremarkable hill south of Rhame, North Dakota there is a fossil site referred to as Medicine Pole Hills. Fossils were first noted from this area in 1922, but no focused collection of fossils occurred at this site until nearly 70 years later in 1989. Teeth and jaws from the multituberculate *Ectypodus* have been recovered from this site (Schumaker and Kihm, 2006) which is believed to be one of the last strongholds of multituberculates in North Dakota.

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NORTH DAKOTA REMAINS ONE OF THE

MOST SEISMICALLY QUIET STATES IN THE NATION

BY FRED J. ANDERSON

North Dakota is not known for its earthquakes. This is good news for us since dealing with severe winter, summer weather, and seasonal flooding takes enough of our time and resources to deal with here in the northern plains! The extreme seasonal variability of our weather and frequency of severe weather-related events like snow and ice-storms, thunderstorms, and nearly annual riverine flooding impact us greatly and will likely continue to do so. This is more than plenty for our communities to deal with. Recent planning and mitigation efforts by state and county officials have increased our ability to successfully navigate our seasonal natural hazards as they continue to occur across the state.

Recently the U.S. Geological Survey, in collaboration with numerous academic institutions and government agencies, has revised and updated the U.S. National Seismic Hazard Model (USGS, 2024). This model describes the chance of a damaging earthquake occurring in the U.S. within a 100-year time frame. The result of this updated work shows, not surprisingly, that the West Coast, particularly California along the San Andreas Fault Zone and northwestern Washington along the Cascades, as areas with the highest chance (i.e. >75%) for a damaging earthquake to occur along with the area surrounding the intersection of the borders of the southeastern states of Missouri, Illinois, Kentucky, Tennessee, and Arkansas (the infamous New Madrid Seismic Zone). Other areas with a high chance of earthquake occurrence are the Sierra Nevada Mountains, along the California and Nevada border, and Yellowstone, where Montana, Idaho, and Wyoming borders meet. North Dakota remains in the most seismically quiet and stable portion of the Continental U.S., and according to the recently updated seismic hazard analysis and modeling, is shown to have a less than 5% chance of experiencing a slightly damaging earthquake in the next 100 years (fig. 1).

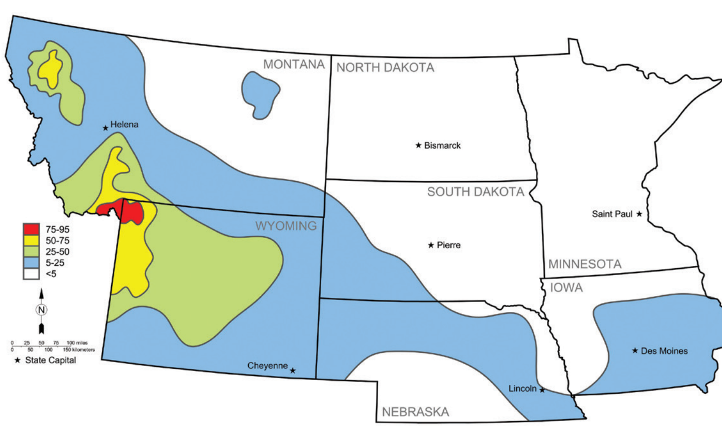

FIGURE 1.
Percent chance for damaging earthquakes in the next 100 years. North Dakota remains in the area with the least chance of experiencing a damaging earthquake (modified from USGS, 2024).

A slightly damaging earthquake is an event that is, "felt by all, with many being frightened and some heavy furniture movement noted, along with a few instances of fallen plaster. Damage is slight," according to the descriptive elements of the Modified Mercalli Intensity scale (which is based on ground shaking and not the size or magnitude of the earthquake) and is assigned an intensity level of VI under this scale.

We've never had that large of an earthquake originate in the state. The largest earthquake in North Dakota was recorded at Huff, located 12 miles south-southeast of Bismarck, on July 8, 1968, with a magnitude of 4.4 and an equivalent Mercalli Intensity value of IV.

This means, for North Dakota, that the new model suggests we have a less than 1 in 20 chance of experiencing a slightly damaging earthquake in the next 100 years. Anything in the realm of 0 to 20% chance is considered very unlikely to occur from a probability standpoint. And, since our state is tectonically stable, continues to be seismically quiet, and has a low population density, it is even more unlikely that we will ever experience the effects of a naturally occurring damaging earthquake. Further, additional seismological research (USGS, 2022) suggests that less than two earthquakes in 10,000 years, with damaging shaking, could be expected to be felt within the state. Good news for North Dakota!

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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.

GEOLOGIC INVESTIGATIONS

Chittick, S.D., 2024, Opeche A Salt Extent and Thickness, Williston Basin, North Dakota, North Dakota Geological Survey Geologic Investigation No. 275

Anderson, F.J., 2024, Offshore Glaciolacustrine Deposits of Glacial Lake Agassiz: The Brenna Formation in Walsh County, North Dakota, North Dakota Geological Survey Geologic Investigation No. 276

Chittick, S.D., 2024, Opeche B Salt Extent and Thickness, Williston Basin, North Dakota, North Dakota Geological Survey Geologic Investigation No. 277

Anderson, F.J., 2024, Offshore Glaciolacustrine Deposits of Glacial Lake Agassiz: The Brenna Formation in Pembina County, North Dakota, North Dakota Geological Survey Geologic Investigation No. 278

LANDSLIDE MAPS - COUNTY SERIES

Anderson, F.J., Murphy, E.C., Maike, C.A., and Moxness, L.D., 2024, Landslide Areas in Mountrail County, North Dakota, North Dakota Geological Survey, County Landslide Map Series, Mountrail-L, 1:125,000.

Anderson, F.J., Murphy, E.C., Moxness, L.D., and Maike, C.A., 2024, Landslide Areas in Billings County, North Dakota, North Dakota Geological Survey, County Landslide Map Series, Billings-L, 1:125,000.

Maike, C.A., 2024, Landslide Areas in Sheridan County, North Dakota, North Dakota Geological Survey, County Landslide Map Series, Sheridan-L, 1:125,000.

LANDSLIDE MAPS

Anderson, F.J. 2024, Areas of Landslides Deering SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Drng SW - I.

Anderson, F.J. 2024, Areas of Landslides Burlington Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brlg - I.

Anderson, F.J. 2024, Areas of Landslides Burlington SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brlg SE - I.

Anderson, F.J. 2024, Areas of Landslides Surrey Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Srry - I.

Anderson, F.J. 2024, Areas of Landslides Minot NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Mnot NW - I.

Anderson, F.J. 2024, Areas of Landslides Dazey NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Dzey NE - I3.

Anderson, F.J. 2024, Areas of Landslides Baldhill Dam Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BlhD - I3.

Anderson, F.J. 2024, Areas of Landslides Minot Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Mnot - I.

Anderson, F.J. 2024, Areas of Landslides Valley City West Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. VlyC W - I3.

Maike, C.A., 2024, Areas of Landslides Anamoose SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Anms SW - I3.

Maike, C.A., 2024, Areas of Landslides Kongsberg NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Kgbg NE - I3.

Maike, C.A., 2024, Areas of Landslides Balfour NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Blfr NW - I3.

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Maike, C.A., 2024, Areas of Landslides Drake NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Drke NW - I3.

Maike, C.A., 2024, Areas of Landslides Drake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Drke - I3.

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Maike, C.A., 2024, Areas of Landslides Butte Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Butt - I3.

Maike, C.A., 2024, Areas of Landslides Kief Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Kief - I3.

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Maike, C.A., 2024, Areas of Landslides Drake SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Drke SE - I3.

Maike, C.A., 2024, Areas of Landslides Martin Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Mrtn - I3.

Maike, C.A., 2024, Areas of Landslides Alkali Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. AlkL - I3.

Maike, C.A., 2024, Areas of Landslides Siebold Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. SbdL - I3.

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Maike, C.A., 2024, Areas of Landslides Sheyenne Lake NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. ShyL NE - I3.

Maike, C.A., 2024, Areas of Landslides Long Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. LngL - I3.

Maike, C.A., 2024, Areas of Landslides Sheyenne Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. ShyL - I3.

Maike, C.A., 2024, Areas of Landslides Turtle Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. TrtL - I3.

Maike, C.A., 2024, Areas of Landslides Peterson Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. PtrL - I3.

Maike, C.A., 2024, Areas of Landslides Pelican Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. PcnL - I3.

Maike, C.A., 2024, Areas of Landslides Pelican Lake SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. PcnL SE - I3.

Maike, C.A., 2024, Areas of Landslides Lincoln Valley SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. LncV SE - I3.

Maike, C.A., 2024, Areas of Landslides Mertz Slough Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. MrzS - I3.

Maike, C.A., 2024, Areas of Landslides Pony Gulch Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. PnyG - I3.

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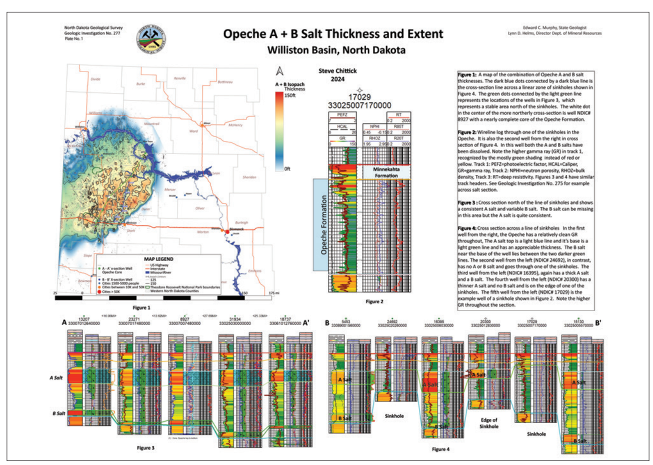
Maike, C.A., 2024, Areas of Landslides Horseshoe Valley Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. HshV - I3.

Maike, C.A., 2024, Areas of Landslides Lincoln Valley Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. LncV - I3.

Maike, C.A., 2024, Areas of Landslides Selz NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Selz NE - I3.

Maike, C.A., 2024, Areas of Landslides Turtle Creek NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. TrtC NE - I3.



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Maike, C.A., 2024, Areas of Landslides Denhoff Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Dnhf - I3.

Maike, C.A., 2024, Areas of Landslides Turtle Creek NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. TrtC NW - I3.

Maike, C.A., 2024, Areas of Landslides Mercer Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Mrcr - I3.

Maike, C.A., 2024, Areas of Landslides Goodrich West Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Gdrc W - I3.

Maike, C.A., 2024, Areas of Landslides Goodrich East Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Gdrc E - I3.

Maike, C.A., 2023, Areas of Landslides Hesper Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Hspr - I.

Maike, C.A., 2023, Areas of Landslides Heimdal Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Hmdl - I.

Maike, C.A., 2023, Areas of Landslides Harvey Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Hrvy - I.

Maike, C.A., 2023, Areas of Landslides Harlow SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Hrlw SW - I.

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Maike, C.A., 2023, Areas of Landslides Grandin Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Grnd - I.

Maike, C.A., 2023, Areas of Landslides Grahams Island Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. GrmI - I.

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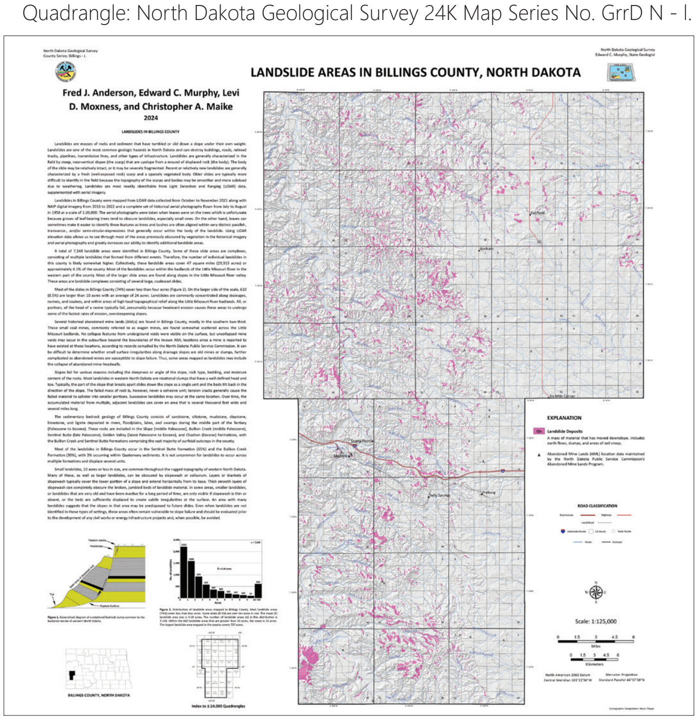
Maike, C.A., 2023, Areas of Landslides Garrison NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Grrn NE - I.

Maike, C.A., 2023, Areas of Landslides Garrison Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Grrn - I.

Maike, C.A., 2023, Areas of Landslides Garrison Dam North Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. GrrD N - I.



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Maike, C.A., 2023, Areas of Landslides Galesburg NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Glsb NW - I.

Maike, C.A., 2023, Areas of Landslides Galesburg Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Glsb - I.

Maike, C.A., 2023, Areas of Landslides Free Peoples Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. FrPL - I.

Maike, C.A., 2023, Areas of Landslides Fort Totten Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. FtTn - I.

Maike, C.A., 2023, Areas of Landslides Flora SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Flra SE - I.

Maike, C.A., 2023, Areas of Landslides Flora Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Flra - I.

Maike, C.A., 2023, Areas of Landslides Fillmore Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Flmr - I.

Maike, C.A., 2023, Areas of Landslides Fessenden West Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Fsdn W - I.

Maike, C.A., 2023, Areas of Landslides Fessenden SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Fsdn SW - I.

Maike, C.A., 2023, Areas of Landslides Fessenden East Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Fsdn E - I.

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Maike, C.A., 2023, Areas of Landslides Emmet NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Emmt NE - I.

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Maike, C.A., 2023, Areas of Landslides Douglas West Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Dgls W - I.

Maike, C.A., 2023, Areas of Landslides Douglas East Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Dgls E - I.

Maike, C.A., 2023, Areas of Landslides Devils Lake Mtn Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. DvLM - I.

Maike, C.A., 2023, Areas of Landslides Daglum SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Dglm SE - I.

Maike, C.A., 2023, Areas of Landslides Crow Hill Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. CrwH - I.

Maike, C.A., 2023, Areas of Landslides Comstock Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Cmsk - I.

Maike, C.A., 2023, Areas of Landslides Coleharbor NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Clhr NW - I.

Maike, C.A., 2023, Areas of Landslides Coleharbor NE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Clhr NE - I.

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Maike, C.A., 2023, Areas of Landslides Colgate Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Clgt - I.

Maike, C.A., 2023, Areas of Landslides Clark Butte SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. ClkB SW - I.

Maike, C.A., 2023, Areas of Landslides Churchs Ferry Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. ChrF - I.

Maike, C.A., 2023, Areas of Landslides Cathay SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Cthy SE - I.

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Maike, C.A., 2023, Areas of Landslides Brinsmade SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brns SW - I.

Maike, C.A., 2023, Areas of Landslides Brinsmade Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brns - l.

Maike, C.A., 2023, Areas of Landslides Bremen Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brmn - l.

Maike, C.A., 2023, Areas of Landslides Brantford NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brnt NW - l.

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Maike, C.A., 2023, Areas of Landslides Brantford Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brnt - l.

Maike, C.A., 2023, Areas of Landslides Blue Hill Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BluH - l.

Maike, C.A., 2023, Areas of Landslides Blanchard Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Blnd - l.

Maike, C.A., 2023, Areas of Landslides Blackwater Lake SW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BkwL SW - l.

Maike, C.A., 2023, Areas of Landslides Blackwater Lake SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BkwL SE - l.

Maike, C.A., 2023, Areas of Landslides Blackwater Lake NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BkwL NW - l.

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Maike, C.A., 2023, Areas of Landslides Black Hammer Hill Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BkHH - l.

Maike, C.A., 2023, Areas of Landslides Bitter Lake Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BtrL - l.

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Maike, C.A., 2023, Areas of Landslides Barlow Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brlw - l.

Maike, C.A., 2023, Areas of Landslides Baker Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Bker - l.

Maike, C.A., 2023, Areas of Landslides Ayr SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Ayr SE - l.

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Maike, C.A., 2023, Areas of Landslides Antelope Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Antl - l.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Keene Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Kene - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Blue Buttes Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BluB - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Blacktail Coulee Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BlkC - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Blue Buttes SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BluB SE - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Ruso Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Ruso - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Croff Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Crff - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Figure 4 Ranch Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Fg4R - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides North Killdeer Mtn Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. NrKM - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Hay Flat Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. HyFl - l3.

Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Lost Bridge Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. LstB - l3.

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Maike, C.A. and Anderson, F.J., 2024, Areas of Landslides Johnsons Corner Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. JhnC - l3.

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Maike, C.A., and Moxness, L. D., 2024, Areas of Landslides Lone Butte SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. LonB SE - l3.

Moxness, L.D., 2024, Areas of Landslides McLeod Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. McLd - l3.

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Moxness, L.D., 2024, Areas of Landslides Venlo Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Vnlo - l3.

Moxness, L.D., 2024, Areas of Landslides Wyndmere NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Wynd NW - l3.

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Moxness, L.D., 2024, Areas of Landslides Wyndmere SE Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Wynd SE - l3.

Moxness, L.D., 2024, Areas of Landslides Elliot Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Elot - l3.

Moxness, L.D. and Murphy, E.C., 2024, Areas of Landslides Killdeer Mountains Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. KdrM - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Squaw Gap Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. SqwG - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Cinnamon Creek Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. CnmC - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Flat Rock Butte Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. FlRB - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Ice Box Canyon Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. IcBC - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Wolf Coulee Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. WlfC - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Grassy Butte Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. GrsB - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Petes Creek Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. PtsC - l3.

York, B.C. and Anderson, F.J., 2024, Areas of Landslides Buckskin Butte Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. BksB - l3.

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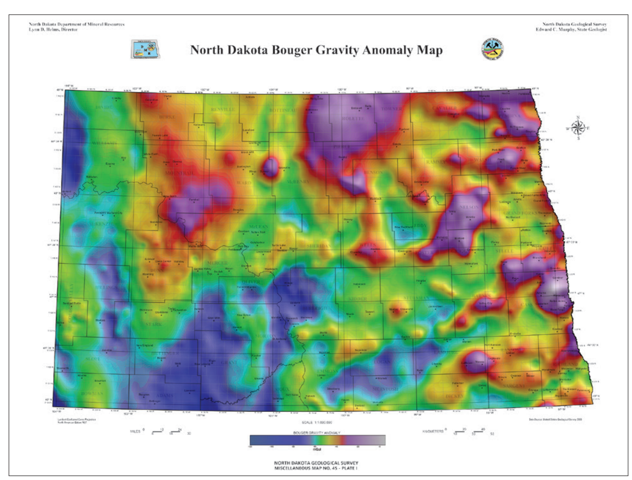

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