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FEATURES

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ON THE COVER:
Jason Mohl and crew (Mohl Drilling Inc.), drilling a critical minerals test hole northwest of Marshall in Dunn County. Photo by Ed Murphy.

CRITICAL CONTEXT:
DRILLING FOR RARE EARTH ELEMENTS AND OTHER CRITICAL MINERALS IN ND LIGNITES

BY LEVI D. MOXNESS

It has been 10 years since a Geo News article first introduced readers to an idea that was beginning to circulate in academic journals and industry – there could be economic quantities of rare earth elements in coal (Seredin and Dai, 2012; Kruger, 2015). A few months later during the 2015 legislative session, the North Dakota Geological Survey (NDGS) would receive funding for a rare earth study. At that time, little was known about concentrations of rare earth elements in North Dakota, since only a handful of samples had ever been examined from the state's estimated 1.3 trillion tons of lignite (Murphy et al., 2006; Palmer et al., 2015). The importance of rare earth elements and many other trace metals to the U.S. became even more clear during international trade disputes over the following years, prompting the U.S. Geological Survey to release a list of the most vital mineral commodities the country imports, grouping them under the term "critical minerals."Reliance on imports is a strategic vulnerability that puts the U.S. at a disadvantage in international trade negotiations and could limit the country's ability to produce vital components for its energy infrastructure and defense systems in the event of a major supply chain disruption.

After many summers of sampling North Dakota's lignite-bearing strata, the NDGS found that some lignites in the state contain very high concentrations of rare earth elements. The most significant enrichment is confined to lignites occurring within two stratigraphic zones, each roughly 30 feet thick. These two horizons are found just below brightly colored ancient soils (paleosols) of the Bear Den Member (Golden Valley Formation) and Rhame bed (Slope Formation) which represent ancient weathering zones that leached rare earth elements into underlying coals, where they are present. Readers can find all seven NDGS reports of investigation on rare earth elements and other critical minerals, which include 35,904 individual elemental analyses from 1,701 samples, organized on one webpage at **www.dmr.nd.gov/dmr/ndgs/critical-minerals**. Also listed on the page are eight Geo News articles detailing progress on the study over the previous decade, including one from our last issue detailing the next stage of the project – filling in gaps in our dataset via a drilling program (Moxness, 2024).

OUT OF THE BADLANDS AND ONTO THE PLAINS

Most of the 2,000+ lignite and other rock samples collected to date have been backpacked out of the badlands of Bowman, Slope, Billings, and McKenzie counties (fig. 1). These samples were collected with a pickaxe and shovel from rock outcrops; steep enough to expose coals to sample, often to the point of being precarious to climb. These outcrops allowed us to effectively sample most of the 2,600-foot stratigraphic thickness of Late Cretaceous through Eocene lignite-bearing rock and build an informed exploration model narrowing down the significant enrichment to the two 30-foot-thick horizons. Outcrops of these two zones have been sampled enough to prove that enrichment clearly extends across several counties, but these narrow stratigraphic windows are simply not exposed often enough to reliably model details like the frequency of lignite occurrence, thickness, and degree of enrichment. In fact, some of the counties with the fewest accessible outcrops (and thus the fewest samples from the NDGS project to date) are underlain by some of the largest areas of the Bear Den Member or Rhame bed just below the surface. In these settings, shallow drilling is the only way to trace these paleosols and explore for enriched coals below them, if they can be reliably identified in pilot holes and electronic logs (fig. 2). One such area of the Bear Den Member occurs in Stark County south of Dickinson where we allocated 10 of the 50 sites from the drilling project, including one just over the border in Hettinger County.

New data to the east is especially important for our understanding of the Rhame bed. Outcrops of silcrete and white clay scattered from Mandan, ND, to Lemmon, SD, to Carlyle, MT have long been treated as the same weathering surface, one we now know is consistently associated with enriched lignites in western Slope County, but these beds might not represent one event horizon.

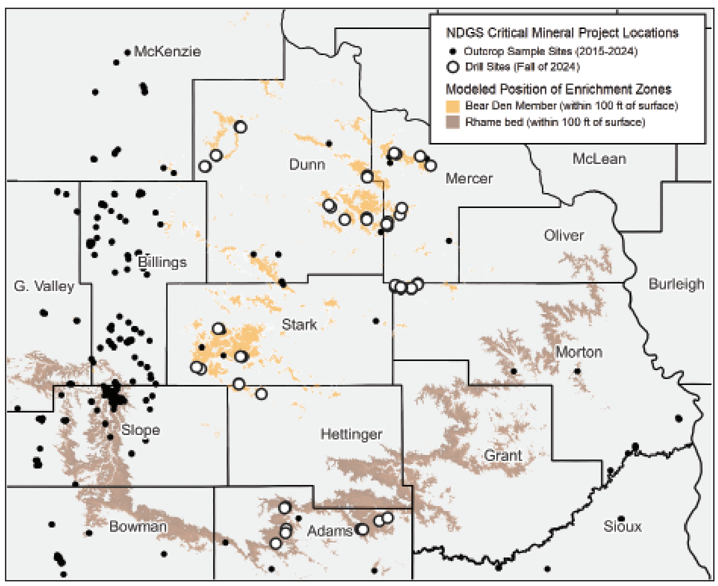

FIGURE 1.
Map of 53 critical mineral drilling sites and previous surface sampling sites.

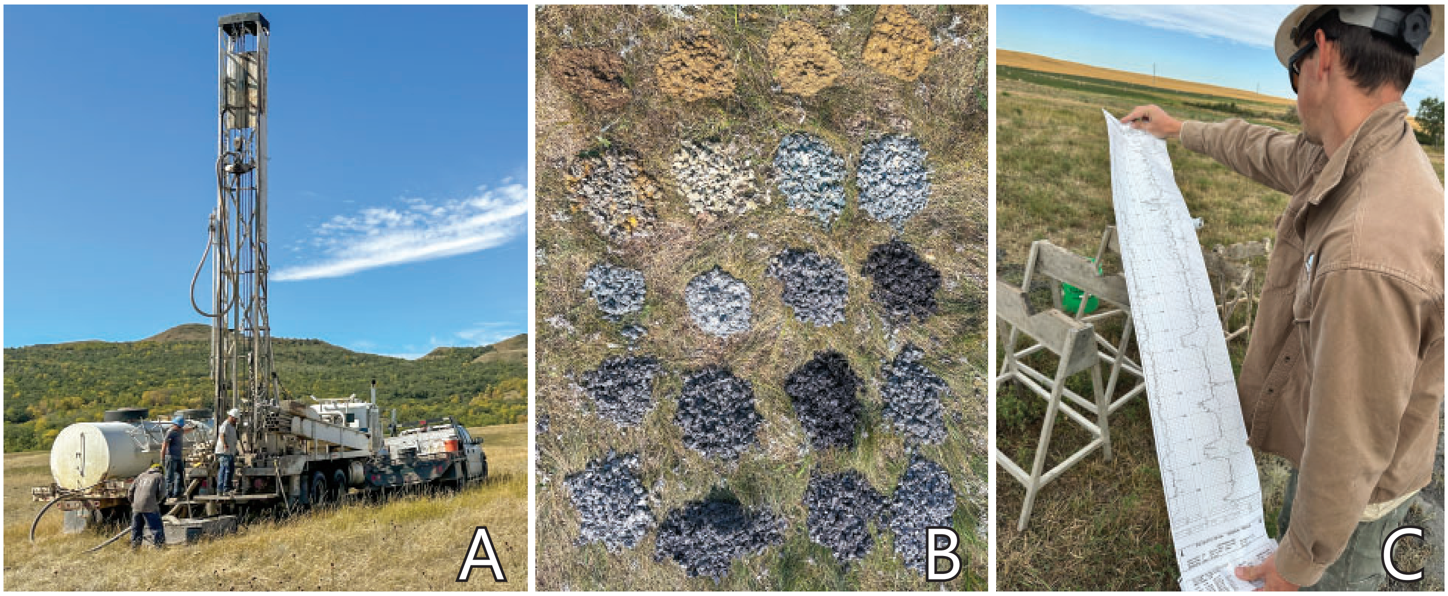

FIGURE 2.

Underground exploration starts with the challenging task of identifying the precise depth of the Bear Den Member or Rhame bed in each hole. Mohl's Drilling of Beulah, ND provided two drilling rigs for the three-week project. **(A)** Jason Mohl and crew drill a pilot hole on the east side of the Killdeer Mountains. As they drill, they take samples of cuttings every 5 feet. **(B)** Piles of cuttings from 100 feet of drilling through the Bear Den Member. Light-colored, "greasy-feeling" clays are indicative of kaolinite, and any coals immediately below are likely to be enriched in rare earths. The exact position and thickness of coals is estimated from gamma and density logs taken once the pilot hole is completed. **(C)** Geologist Levi Moxness examines a log, produced by Century Wireline Services, to identify a target interval for coring.

What would this mean for potential rare earth enrichment in Adams, Hettinger, Grant, and Morton counties? Even using all 50 holes to correlate a paleosol across half the state may not be enough to answer that question, but nine holes were allocated to exploring the bed through Adams County.

ADDING DATA NEAR COAL COUNTRY

North Dakota's five operating thermal coal mines target thick coals in the Sentinel Butte Formation. One hundred feet or more above them is the Bear Den Member of the Golden Valley Formation, or at least that is where it would occur had it not been eroded away in the area around the mines. The Rhame bed is likely several hundred feet below them, if it is present at all deep underground in Oliver, Mercer, and McLean counties. Although these two zones of extreme rare earth enrichment do not occur at the operating thermal coal mines, the existing infrastructure there means concentrations of rare earths would be economic at far lower levels. The upper and lower margins of the thick coals at the mines contain elevated levels of rare earths and other important critical minerals like gallium and germanium (Kay et al., 2024). If the U.S. is serious about building the nation's first coal-hosted critical mineral extraction facility, North Dakota's existing mines make a lot of sense. They are already incidentally mining several tons of these strategic minerals every day.

Should an extraction facility be built at one or more of North Dakota's existing lignite mines, highly enriched seams within reasonable transport distances may also be of interest. A significant area of the Bear Den Member is still in place in western Oliver and eastern Dunn counties. The NDGS had sampled a few outcrops in this area, but most simply did not have enough strata exposed below the base of the kaolinite to determine if coals were even present without serious excavation. Drilling is far more efficient for this purpose, and the NDGS allocated 17 holes from the program to do strategic randomized drilling through the Bear Den Member in the unexplored area just west of the state's coal mines.

FOCUSING IN ON LATERAL VARIABILITY

During surface sampling in 2022, thin coals near the base of the Bear Den Member were found to contain rare earth element concentrations up to 30 times higher than normal U.S. coal (Murphy et al., 2023). These levels of enrichment are amongst the highest known from coal in North America, and all our sampling work to date suggests such concentrations only occur in narrow stratigraphic zones immediately below a white kaolinitic claystone, like the one mined by Hebron Brick Company in northwestern Morton County. In their western clay pit and the scattered outcrops surrounding it, these highly enriched coals vary in thickness but are usually less than one foot thick. Despite their extreme concentrations of rare earths, coals like these may not ever be viable targets unless they can be traced laterally and found where they are consistently thicker. Fortunately, this is not some uncommon, idealized scenario, as lignites in the Williston Basin are known to thicken and thin over short distances. A six-inch-thick coal could be two feet thick a few hundred yards away and completely gone the same distance in the opposite direction, but it is rare to have outcrops continuous enough to see it. Drilling provides the opportunity to choose where and how frequently to capture a snapshot of this variability without needing to rely on lucky exposures.

There is a second scenario to investigate when looking at the lateral variability in these zones. The weathering profiles themselves formed on ancient landscapes with topography, so there is a possibility that a thick coal exists in one position where the weathering profile formed too

FIGURE 3.
Once intervals of interest have been identified from cuttings and electronic logs, a second hole is drilled a few feet away to retrieve core. **(A)** John Mohl inspects a 15-foot section of core containing the 10-foot thick Harmon lignite and several feet of Rhame bed silcrete below, complete with its characteristic fossil root casts (inset). **(B)** State Geologist Ed Murphy describes a core of the Bear Den Member, noting distinctive features like bright orange iron oxide staining (inset). **(C)** Geologists Ned Kruger (left) and Adam Chumley (right) select core samples for ICP-MS analysis. Jason Mohl (rear) is coring the next interval. The remaining core is boxed for transport to the North Dakota Geological Survey's Core Library in Grand Forks.

far above to enrich it, but nearby, on a lower portion of the ancient landscape, the same thick coal was not too deep to receive the descending rare-earth enriched waters during the weathering event. The Harnisch lignite is one such bed. At five to six feet in thickness and just 20 feet from the base of the kaolinite in the area around Hebron Brick Co.'s west clay pit, the NDGS allocated 12 holes to do the program's most closely spaced drilling in this area to add important data on the variability of 1) the thin, extremely enriched coals previously identified in the center of the target zone, to see if they thicken (or disappear) laterally, and 2) the relative position of the Harnisch lignite bed and weathering zone of the Bear Den Member, to see if there are areas where these two horizons are close enough together to enrich this much thicker lignite bed.

One core from this area may also provide new insight into another interesting question. Where do the rare earths go when there is no coal to "catch" them? We have assumed they are somewhat evenly distributed through the underlying clays but have allocated most of our sampling focus the past few years to the lignites. We plan to perform a more detailed analysis on one core from the Hebron area which had no thin coal between the Bear Den and Harnish lignite to understand how enriched the clays themselves can become, and at what depth peak enrichment occurs. Peak enrichment should correlate to the optimal depth for which a coal should occur to receive the most enrichment.

The NDGS allocated another seven holes to a similar effort to trace known enrichment in the Killdeer Mountain area. Site 266 (Murphy et al., 2023) showed three thin, enriched coals at the base of the Bear Den Member, but a lack of nearby outcrops prevented us from saying much else about this unique site. Are coals more frequent or thicker as you get closer to the center of the basin? Two more holes in the same quarter section cored this same interval, and two other sites along the slopes of the Killdeer Mountain mesa added context a few miles to the northeast.

NEW FINDINGS COMING SOON

In total, over 8,592 feet were drilled between 53 pilot holes and 29 core holes over the course of 15 days in September and October 2024. We recovered 941 feet of core and 469 samples of cuttings were collected (fig. 3). So far, 169 samples have been submitted for ICP-MS analysis, results from which will be detailed in upcoming NDGS reports of investigation and are sure to be featured in upcoming Geo News articles.

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UP TO FOUR HUNDRED MILLION BARRELS OF RECOVERABLE OIL

IN THE MIDDLE THREE FORKS FORMATION IN NORTHEAST MCKENZIE COUNTY, NORTH DAKOTA

BY TED STARNS AND TIM NESHEIM

The North Dakota Geological Survey has recently completed a series of case studies evaluating the middle Three Forks Formation (2nd bench) resource potential in and around northeastern McKenzie County. A dilemma that has held back full-scale development of the middle Three Forks Formation (middle Three Forks) is whether its co-development adds to long-term oil production, or simply accelerates the rate of recovery. In other words, producing the same amount of oil, but at a higher rate. A recently published North Dakota Geological Survey study investigated 593 wells in fifty-one 1,280-acre drilling spacing units and defined a contiguous area of potential development that spans ~275,000 acres. This area holds the potential for 600+ new middle Three Forks development wells with an estimated ultimate recovery between 165 – 410 million barrels of oil. The results of the study indicate that developing the middle Three Forks Formation in addition to the Middle Bakken Formation (Middle Bakken) and upper Three Forks Formation (upper Three Forks) can increase long-term recovery, meaning more oil can be produced.

Following the 2006 discovery of the Parshall Field in western North Dakota, oil and gas companies primarily targeted the Middle Bakken with horizontal wells. As understanding and investment grew in the play, the underlying rock units in the Three Forks Formation were targeted and proven to hold reserves. The upper Three Forks developed into a second established exploration and development target during 2008-2010. Beginning in 2013, the middle Three Forks also began to be targeted. To date, over 360 horizontal wells have been drilled and completed targeting the middle Three Forks that have produced over 92 million barrels of oil and 238 billion cubic feet of gas. While drilling and completion activity in the middle Three Forks has been relatively steady (fig. 1), it has only represented a small fraction of the drilling activity compared to the overlying upper Three Forks and Middle Bakken.

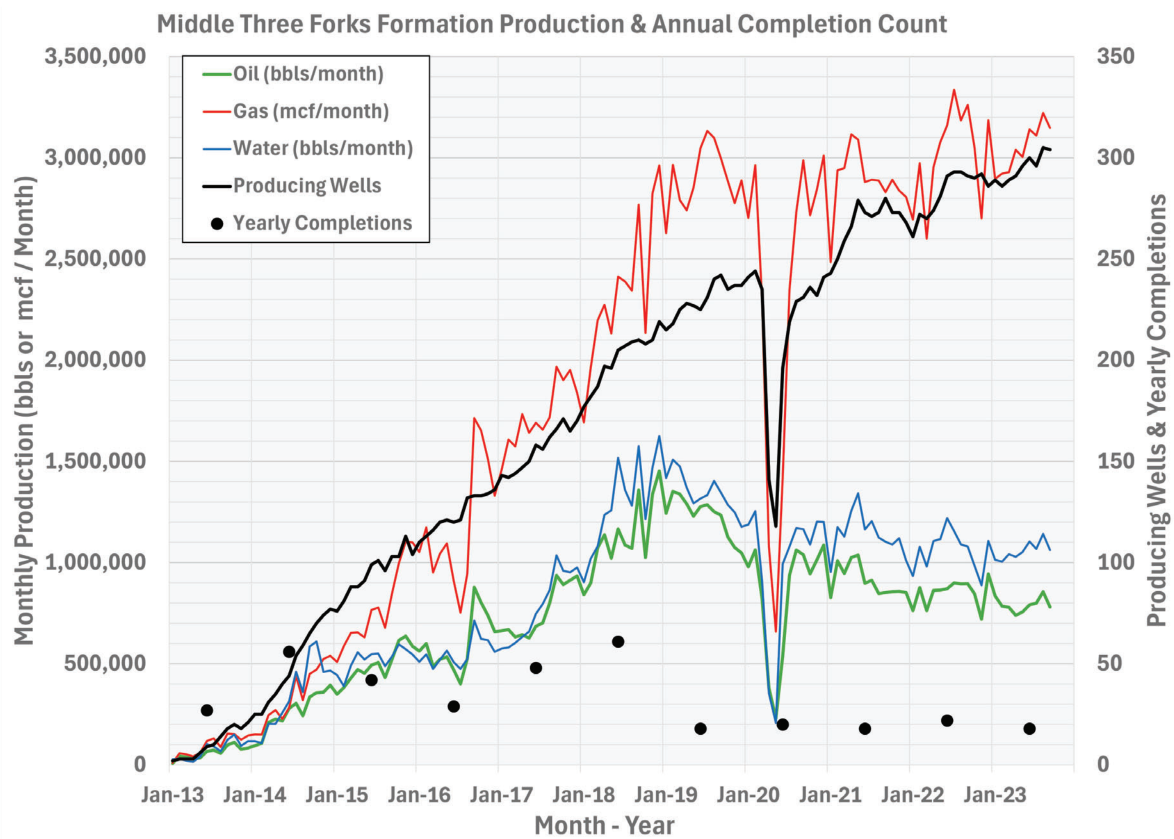


FIGURE 1. Monthly cumulative production of oil, gas, and water from middle Three Forks Formation horizontal wells, along with the active producing well count and the number of middle Three Forks Formation wells completed each year since the beginning of its development.

To evaluate the contribution of the middle Three Forks, 1,280-acre drilling spacing units with Middle Bakken, upper Three Forks, and middle Three Forks wells were compared to drilling spacing units with only Middle Bakken and upper Three Forks wells. Each well within a drilling spacing unit was analyzed to determine its three-year cumulative oil production and estimated ultimate recovery (e.g., fig. 2). By combining the production data of wells within each drilling spacing unit, a comparison was made between drilling spacing units containing middle Three Forks development wells and adjacent drilling spacing units without middle Three Forks wells.

One such comparison, in northeast McKenzie County (T153N/R95W, T153N/R94W, T152N/R95W, & T152N/R94W), illustrates drilling spacing units with middle Three Forks wells that produce more oil than adjacent drilling spacing units without middle Three Forks wells (fig. 3). Note the increased early production and estimated ultimate recovery in drilling spacing units B & C compared to D & E. Drilling spacing units B & C have two to three middle Three Forks horizontal wells and are expected to bring on an additional ~1.5 million barrels of oil from the middle Three Forks alone.

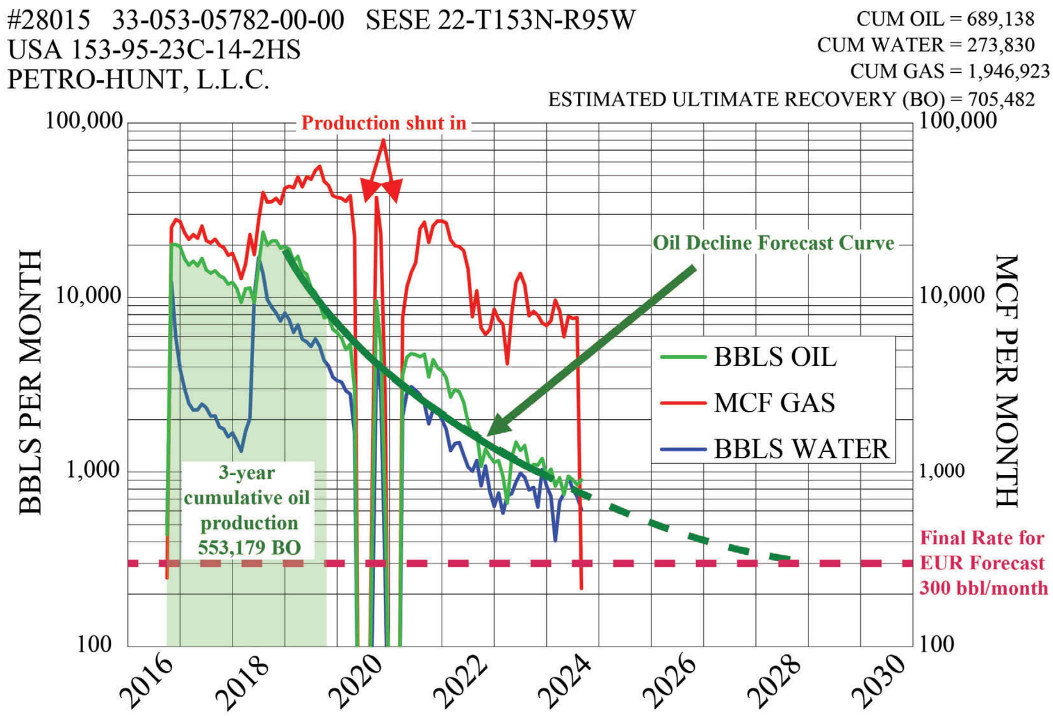


FIGURE 2. An example of production from a middle Three Forks well in McKenzie County with exceptional performance.

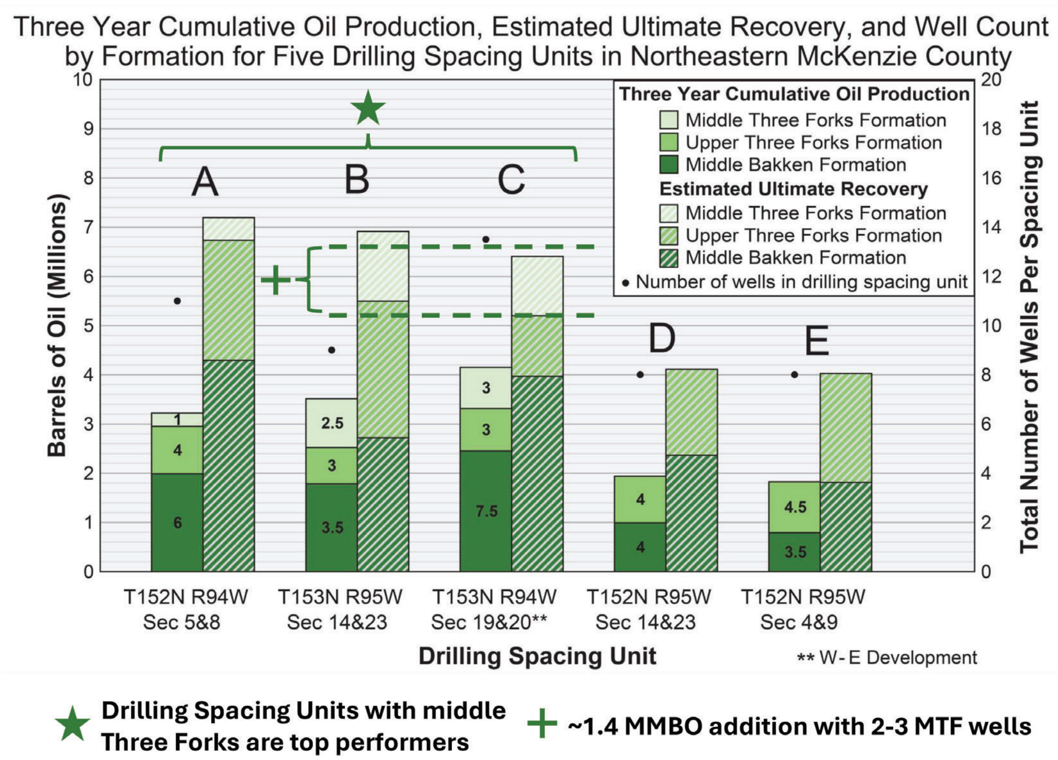
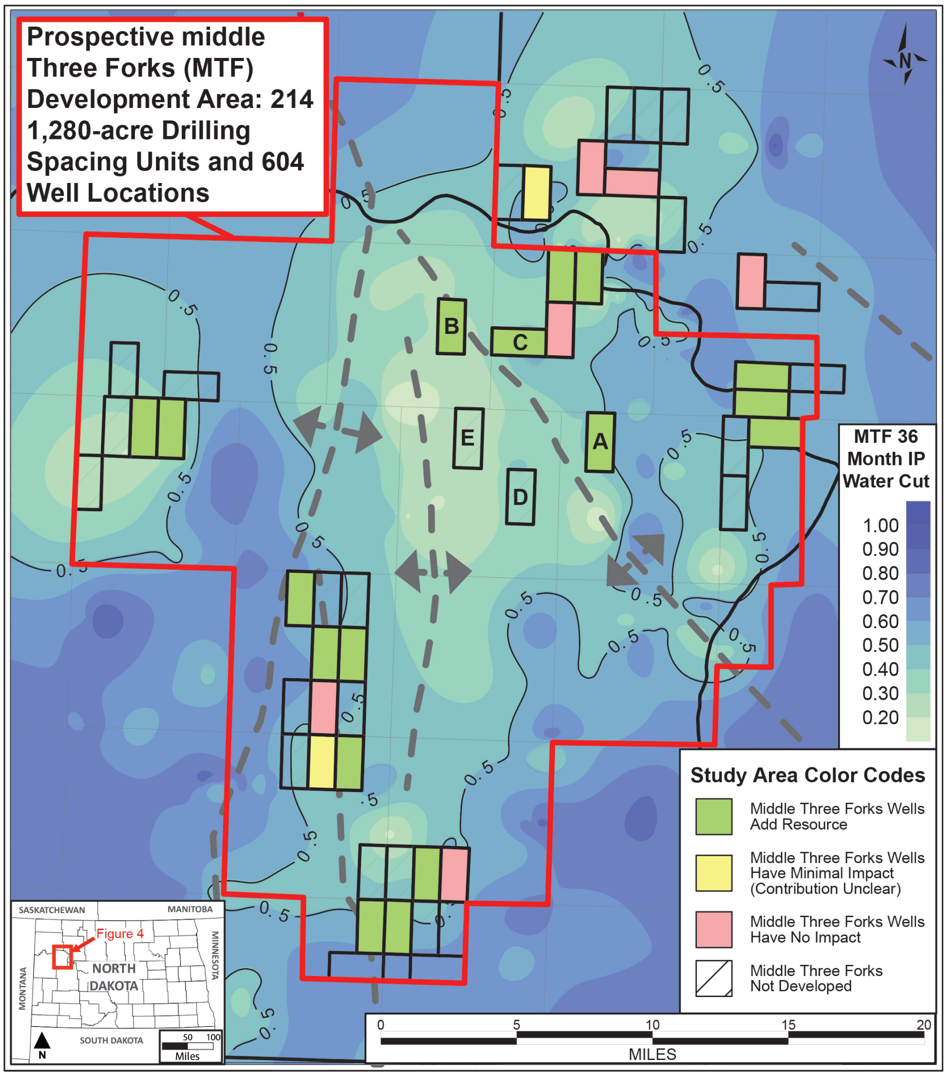


FIGURE 3. A comparison of the sum of the first three years' production and estimated ultimate recovery forecasts for the wells within five different drilling spacing units (A-E, locations on figure 4) in northeastern McKenzie County.

This study investigated 25 drilling spacing units with middle Three Forks horizontal wells. Of those, 17 spacing units exhibited a clear volumetric addition of oil produced with the development of the middle Three Forks (68%), six did not (24%), and in two (8%), the contribution was unclear (fig. 4). The results of this study indicate that developing the middle Three Forks, in addition to the Middle Bakken and the upper Three Forks, adds to long-term oil recovery on the order of 1 – 2 million of barrels per 1,280-acre spacing unit.

Seventy middle Three Forks wells were evaluated (~20% of total middle Three Forks wells), with a 50th percentile estimated ultimate recovery of ~430,000 barrels of oil. Assuming three middle Three Forks wells can be drilled in each available 1,280-acre drilling spacing unit within the contiguous area outlined in this study, the middle Three Forks in northeast McKenzie County has the potential to host an additional 600+ drilling locations and produce between 165 – 410 million barrels of oil (table 1).



This conservative estimate of potential recoverable oil is limited to the area investigated in northeastern McKenzie County, and the area of productive middle Three Forks reservoir has the potential to expand with continued development. As the Bakken – Three Forks petroleum system sees steady development in the decades to come, the middle Three Forks (2nd bench) reservoir is a prime candidate for continued infill drilling to provide resource for the State of North Dakota and all stakeholders. Additional details can be found in North Dakota Geological Survey publication RI-136.

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FIGURE 4.

Study area results and the contiguous area which holds potential for development, overlain on a map of the water cut from the first three years of production from middle Three Forks Formation horizontal development wells. The drilling spacing units presented in figure 3 are labeled A-E. Also noted are major regional anticlinal structures in gray dashed lines.

TABLE 1: Potential recoverable oil ranges for the prospective area outlined in northeastern McKenzie County.

Wells in Data Set	Middle Three Forks Estimated Ultimate Recovery (EUR)		
	10th Percentile	50th Percentile	90th Percentile
70	274,111	430,262	682,608
Potential Remaining Drilling Locations	Prospective Area* middle Three Forks EUR		
	10th Percentile	50th Percentile	90th Percentile
600	164,466,600	258,157,200	409,564,800
~165 - 410 Million Barrels of Recoverable Oil			

*See Figure 4 for prospective area

25 YEARS OF PUBLIC FOSSIL DIGS

BY JEFF J. PERSON

July 15, 2024 marked 25 years of public fossil digs with the North Dakota Geological Survey paleontology department. The program started small, as most things do, to eventually become one of the country's largest, if not the largest, public fossil dig programs. Over these last 25 years many important and unique specimens have been found. From saber-tooth cats preserved with bite marks, to swimming reptiles that are brand new to science, to small mammals with teeth so small they must be glued to the head of a pin, the discoveries of the public dig program are broad and highly significant. The success of the public dig program can be measured in several ways including longevity, interactivity, productivity, and economic impact. But no matter how you measure success, this program has been a boon for North Dakota paleontology and this state's citizens.

2000-2007

The first public dig took place in northeast North Dakota in the Pembina Gorge near the town of Walhalla, ND (fig. 1). It started on July 15, 2000 and lasted seven dig days. The focus of this dig was the 80-million-year-old Pierre Formation which was deposited in a shallow, inland sea. The participants found a variety of creatures including fish, birds, giant squid, and a large 20-foot sea monster called a mosasaur.

WALHALLA Mountaineer

SERVING PEMBINA AND CAVALIER COUNTIES

VOLUME 103. A Pembina County Publication Walhalla Mountaineer, Walhalla, ND. 58282 Tuesday, July 25, 2000 NO. 42.

Fossil Dig!

Dr. John Hoganson, Paleontologist with the Geological Survey Department, points to a bone testing area at the dig site last Wednesday.

First-ever state-sponsored fossil dig held in Pembina Gorge near Walhalla July 15-23

The first-ever state-sponsored fossil dig was held in the Pembina Gorge west of Walhalla July 15-23. Fifty fossil diggers including 35 from North Dakota, one from Texas, Nebraska, Arizona and Washington, two from Virginia and Wisconsin, six from Minnesota and one from Norway participated in the event. It was sponsored by the North Dakota Geological Survey, North Dakota Department of Tourism, and the North Dakota Parks and Recreation Department.

The project included five separate digs: a 3-day dig July 15, 16 and 17; three 1-day digs July 19, 20 and 21; and a 2-day dig July 22 and 23. The dig was conducted to boost tourism and economic development in northeastern North Dakota, according to Joanne Burke of Bismarck, who is Deputy Director of the North Dakota Tourism Department. Dr. John Hoganson, Paleontologist with the Geological Survey oversaw the dig, which was held at the Mosasaur fossil dig site in the Pembina Gorge. The site overlooks the north fork of the Pembina River, and is on the road to the Nunedahl area.

Fossilized remains of a number of marine creatures discovered include Mosaurs, Plesiosaurs, Hesperornis, Bulldog Tarpons and Enchodus.

Top photo: three "Walhalla diggers" Ted Dunnigan 3rd from left, Pastor and Mrs. Fred Westerhold far right. Lower photo: Scenic Pembina Gorge across the road from dig site.

FIGURE 1.
Front page of the *Walhalla Mountaineer* dated July 25, 2000, detailing the first public fossil dig run by the North Dakota Geological Survey.

Over the next several years the public dig program began to gather steam with one, two, or as many as three digs being held during the summer months (fig. 2). The digs are always held while public school is on summer break so kids as young as 10 can dip their toes in the experience of digging for fossils. During these first years of the public fossil digs, the NDGS paleo program did not have a presence on social media and very little effort was made to advertise these events. Consequently, these digs were only known through word of mouth, registration was merely a formality, and "walk-ins" were easily accommodated. The number of daily participants varied but never got out of hand. Two NDGS staff paleontologists were able to supervise and assist all those who attended. During this time the term "eco-tourism" was being used across the country as a way for programs to leverage interest in natural resources to bring tourists into the region. The public fossil dig program is a great example of eco-tourism.

2008-2014

Now an established program, the digs started to gather a little steam as word of mouth began to spread. With a more established program and a regular number of digs each summer a backlog of what had been collected started to build. Although slowly at first, it eventually became evident that something would need to be done to remedy the situation. Through these seven years, staff paleontologists experimented with age minimums to attend the digs as well as how much time the younger kids could focus their attention on the task at hand without becoming bored and (sometimes) destructive. Over several years we settled on a minimum age of 10 years for family half days and a minimum of 15 years with an accompanying adult for full days.

During the summers of 2011 and 2012, we found that some people would register for the digs but would not show up. It would not happen very often but did happen enough to be a problem. In one instance, of the 8 people registered to dig at one of our locations on one day, only one person showed up. While this may have been a treat for the only person digging that day to get the full attention of two paleontologists, we knew others wanted to attend these digs but could not because of full registration.

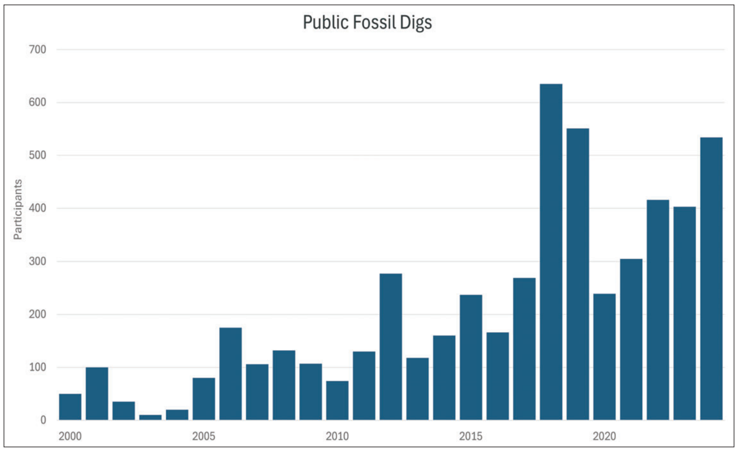

FIGURE 2.
Registration for the public fossil digs is shown to have several "jumps." Between 2000 and 2011, numbers were relatively low. A significant increase in registration occurred between 2012 and 2017, with a final jump occurring between 2018 and 2024.

Between 2000-2014 the fossil digs were free to attend. The only cost to participants was travel, food, and lodging costs they might encounter while digging at various locations across the state. One of the underlying tenets of the North Dakota Geological Survey fossil dig program is that we remain affordable to all who might have an interest in the fossil history of the state. If a dig is too costly to attend, we are eliminating a segment of the population which is something we fundamentally do not want to do. To try to remedy this problem, in 2015 a small $10 per person charge was issued to registrants but was refunded to those who showed up. But the fee wasn't enough to give others pause before deciding not to show up because they overslept. This fee was increased to between $40 and $60 depending on the dig. This fee is used primarily for road repair, port-a-potty rentals, equipment replacement (brushes, trowels and such), and purchasing certain consumables like plaster and plaster bandages.

Of those early years, 2014 was our busiest, with seven digs throughout the summer. All the digs were short in length, but we visited many locations, some more than once, throughout the summer. This turned out to be too many digs as the staff paleontologists were spread too thin and we deemed that many digs in one summer to be unsustainable.

2015-2024

The last 10 years of these public digs have seen only a few changes to the formula. We now have an established dig fee for each location, and we have landed on the ideal number of participants per day to be 10. This number seems to work for a variety of reasons. The ratio of participants to staff is correct so people feel they are getting adequate direction and attention from staff, and do not feel ignored. Ten participants also make travel to and from the dig site more comfortable for people and gear in our vans. Finally, most of the locations where we dig cannot handle large numbers of people digging at one time. There is just simply not that much room in these quarries.

Interest in the digs has increased nearly exponentially. In the early years of the program, when registration was merely a formality, participation for the summer was fewer than 100. As the years went by, and word began to spread, participation increased and the need for registration became much more apparent. In July of 2017, the *New York Times* published an article about our public fossil dig program which caused interest in our little program to surge (Boyd, 2019). In 2019 over 500 recipients were on our dig-notification list (Boyd, 2019), but over the last five years, that number has grown to nearly 2,400. Since most people do not come to these digs alone, but with at least one other person, that number likely represents a potential of nearly 5,000 or more people who are interested in this program. Registration for dig spots has transferred from phone calls to being entirely online. This online registration has streamlined the process and highlighted just how interested people are in participating in the program. The registration for 2024 tickets opened for the general public in early February and our most popular dig sold out in four minutes with the remainder of the summer tickets sold out just 10 minutes later.

In response to the dramatic increase in interest over the last few years, the number of days of digging in the field has increased substantially. Between 2000 and 2017, the number of public fossil dig field days averaged 16. Between 2018 and 2023 the average increased to 42, nearly triple that of the number before the *New York Times* article. An increase in time spent digging for fossils leads to a higher number of fossils collected. Without an increase in staff time dedicated to processing the fossils collected, the backlog of unprocessed material would soon be overwhelming. At the end of 2022, there were a total of 695 field jackets waiting to be prepared, plus surface collected material to be cleaned and over 200 buckets of concentrate to be wet screened. This was enough backlog material to easily fill a 50-foot semi-truck trailer.

25 YEARS OF RESULTS

The fruits of the labor from all these years of public fossil digs are many. Due to the large backlog of unprepared and unwashed collected material, it is presently not possible to count the number of fossils added to the NDGS collections due to this program. However, it could easily be estimated to be thousands if not tens of thousands of fossils collected over the last 25 years. Though the focus has been on collecting fossils of vertebrate animals, many fossils of plants and invertebrate animals have also been collected in large numbers.

There have been many great finds as a direct result of the public fossil digs. These findings started immediately with the rare discovery of a pen bone from a giant squid during the first dig in 2000. This initial find was followed by numerous others including large mosasaurs (*Jormungandr*), early bears (*Eoarctos*), early mammals (*Glasbius*), rare dinosaurs (fig. 3), and new fossil animals yet to be described.

Many animals that are brand new to science have been discovered during these fossil digs. While most of the work

FIGURE 3.
One of a dozen *Tyrannosaurus rex* teeth that have been discovered by public fossil dig participants at our dig south of Bismarck-Mandan. Note the two lines of serrations on the tooth. Scale is in centimeters. (NDGS 21315)

done to name and describe these new species is done after they are collected, there is no doubt that without this program most of these species would have never been discovered or collected. As of this writing, eight new species and one new taxon based on a bird eggshell have been named as a result of the public fossil dig program (e.g., Korth et al., 2019a, 2019b, 2020, 2023). One new species of rabbit and at least two new dinosaurs, previously unknown to science, are in the works with many more on the way as more material is prepared and studied. Associated with naming new species is the study of certain animals or entire faunae. These studies are published usually through newsletter articles or peer reviewed journals. There have been dozens of these articles done on various animals and faunae collected through the public fossil dig program. The addition of knowledge about what animals looked like and how they may have interacted with other animals can also be traced to specimens collected during these public fossil digs (e.g., Hoganson and Person, 2010; Wilson et al., 2016; Boyd et al., 2017).

Informing the North Dakota public is a major function of what we do at the North Dakota Geological Survey paleontology program. In the fall, winter, and spring months we give countless tours to school groups, give talks to local and national groups, as well as participate in programs such as Science Olympiad and Earth Day. The Fossil Dig program has also been the focus of, and featured in numerous newspaper articles and television stories throughout its 25-year history including the *New York Times* and the *TODAY* show. All these outreach activities allow us to educate the public and spread the word about the importance of fossils in North Dakota, which helps us protect this non-renewable resource.

Over the last 25 years, the North Dakota Geological Survey has hosted 83 public fossil digs, with approximately 5,300 tickets (each ticket represents one person for one day). Given that most people attend 2 days, the final number of individuals is closer to 3,000 people. Calculating the number of unique individuals that have come to the fossil digs is a little tricky. Some people attend one dig for one day for one year, other people come back for weeks at a time every year. The public fossil dig program has also teamed with the Bismarck and Mandan Public School system and offers a day at one of the fossil sites for summer biology students. This is just one of our many outreach and education outlets for the local area (Person, 2019). Over the last ten years, more than 350 students have attended these dig days. If these students are also included in the total number, it is safe to say that over the last 25 years, the public fossil digs have touched the lives of over 3,300 people. The number of labor hours this translates to is simply astounding. Since 2000, 5,300 dig participants working 7-8 hours per day has resulted in over 37,000 hours of work being done by the public to help collect fossils in North Dakota. It would take 18.5 years for one person working 40 hours per week to accomplish that feat.

The geographic participation is approximately 50% from within North Dakota and 50% from outside of the state (Boyd, 2019). From Washington state to California in the west and from Massachusetts and Florida in the east, we are attracting people from all four corners of the contiguous United States. Since we want to educate North Dakota citizens about paleontology and bring in tourists from out of state, we feel this is a great balance of where people are coming from. We have had participants from at least 45 states (fig. 4) and have had some join us from as far away as Italy and Norway.

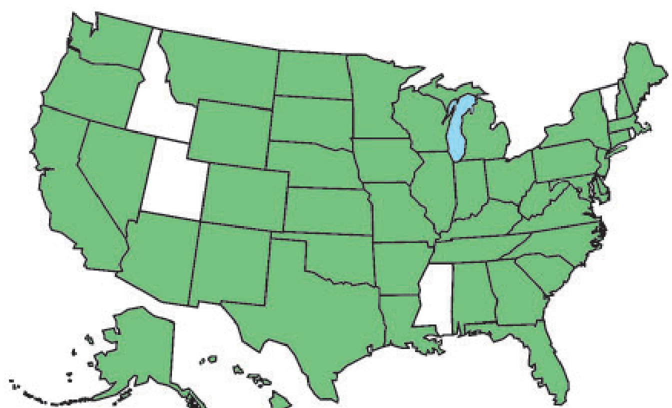

FIGURE 4.
Geographic participation in the public digs covers 45 states (green) over the last 25 years. Participants from outside the United States include Norway, Italy, and American Samoa.

The fossil dig program has also had an impact on the local economy. The North Dakota Tourism Department reports the average tourist spends $120 per day in North Dakota based on 2021 numbers (personal communication). We have surveyed the dig participants and many of the out-of-staters spend an average of four days in North Dakota. Additionally, many of the North Dakotans spend two days exploring, often in a different part of the state from which they live. This results in an average time spent of three days. Which means that over the last 10 years, diggers have spent $1.4 million in North Dakota.

The North Dakota Geological Survey has placed 25 paleontology exhibits across the state (fig. 5) (Hoganson, 2005; Boyd, 2017; Barnes and Boyd, 2022). Most of these exhibits contain or highlight specimens collected during the public fossil dig program. The goal of these exhibits is to keep fossils near where they have been collected and to educate the local and touring public about what fossil plants and animals once inhabited the area.

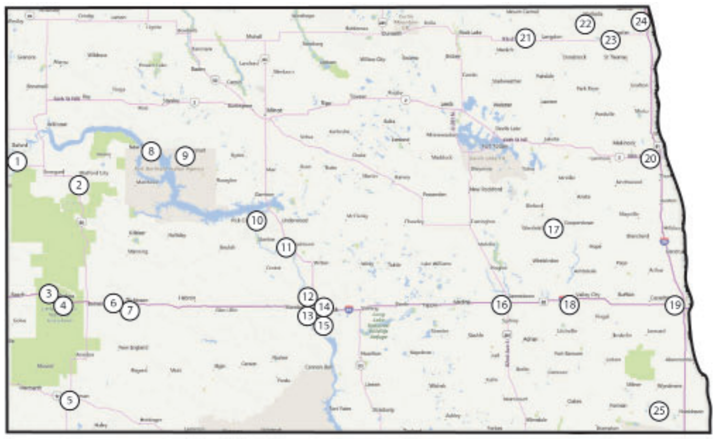

FIGURE 5.
Paleontological and geological exhibits throughout North Dakota that the North Dakota Geological Survey paleontological resource management program has assisted in developing as a part of the "A Fossil Exhibit in Every Town" program. Background layer from Bing Road Maps. **KEY:** **(1)** Missouri-Yellowstone Confluence Interpretive Center, Buford; **(2)** Long X Trading Post Visitor Center, Watford City; **(3)** Theodore Roosevelt National Park South Unit Visitor Center, Medora; **(4)** North Dakota Cowboy Hall of Fame, Medora; **(5)** Pioneer Trails Regional Museum, Bowman; **(6)** Dakota Prairie Grasslands, Medora Ranger District Office, Dickinson; **(7)** Dickinson Dinosaur Museum, Dickinson; **(8)** Three Affiliated Tribes Museum, New Town; **(9)** Paul Broste Rock Museum, Parshall; **(10)** United States Army Corps of Engineers Headquarters, Riverdale; **(11)** McLean County Museum, Washburn; **(12)** Industrial Commission – North Dakota Geological Survey and Oil and Gas Division Headquarters, Bismarck; **(13)** North Dakota Heritage Center & State Museum, Bismarck; **(14)** Dakota Prairie Grasslands Supervisor's Office, Bismarck; **(15)** Bismarck Municipal Airport, Bismarck; **(16)** National Buffalo Museum, Jamestown; **(17)** Griggs County Museum, Cooperstown; **(18)** Barnes County Museum, Valley City; **(19)** North Dakota State University, Stevens Hall, Fargo; **(20)** University of North Dakota, Harold Hamm School of Geology and Geological Engineering, Leonard Hall, Grand Forks; **(21)** Cavalier County Museum, Dresden; **(22)** Walhalla Public Library, Walhalla; **(23)** Icelandic State Park, Cavalier; **(24)** Pembina State Museum, Pembina; **(25)** Lidgerwood Public Library, Lidgerwood.

The public fossil dig program has supported 12 paleontology interns since 2013. Both field and collections/lab-based summer internships have been provided, helping to educate future paleontologists and giving them on-the-job experience for their future careers.

After 25 years of collecting and educating the public about the fossil flora and fauna of North Dakota's past through the North Dakota Geological Survey fossil dig program, we can measure great success no matter what metric you use. All the above topics reflect a prosperous and thriving program with room to grow. If you are reading this article and haven't joined us on a fossil dig, why not? Our digs run every summer from June through August, and we have digs in the western, central, and eastern portions of the state. Check out our website (**www.dmr.nd.gov/dmr/paleontology/fossil-digs**) where we have answers to frequently asked questions, photos of past digs, upcoming dig information, and links to registration.

We would like to meet you next summer!

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JOIN US IN JUNE, JULY, AND AUGUST ON SITES ACROSS NORTH DAKOTA IN THE SEARCH FOR FOSSILS!

2025 PUBLIC FOSSIL DIGS

ONLINE REGISTRATION FOR ALL DIGS (FIRST COME, FIRST SERVED!):

Opens February 1 at 10am Central @ www.ndpaleofriends.org

Take a prehistoric fishing trip to the northeastern corner of the State, in the beautifully scenic Pembina Gorge – home of our newest State Park. Sea monsters swam in the Western Interior Seaway 80 million years ago, in this Pierre Formation location.

Travel back in time to when dinosaurs roamed the land at the Bismarck Area site, located south of Bismarck-Mandan in the Hell Creek Formation. These 67-million-year-old creatures range from the fearsome *Tyrannosaurus*, horned *Triceratops*, and the ever-present duck-billed *Edmontosaurus* – along with other creatures that lived underfoot (crocodiles, turtles, mammals, and more).

You won't need a fan-boat to view the swamps of western North Dakota, but you may need some good sunblock! The Paleocene (55-65-million-year-old) Sentinel Butte and Bullion Creek Formations hold a variety of swampy denizens, including crocodiles, giant salamanders, fish, clams, snails, and more.

We won't be visiting the Oligocene Dickinson area this year. The site weathers out slowly, and needs to rest for a year or two before we head back again.

GENERAL DIG INFORMATION

- All fossils collected on these digs go to the North Dakota State Fossil Collection and are used for educational and research purposes.
- Participants must bring their own lunches at all three dig locations.
- Shade tents and porta-potties will be available on-site.
- The Experienced 2-Day Site Closing Session may finish early on the second day.
- Our digs have a minimum age of 15 years for a Full Day & 10 years for a Family Half-Day. No digs for children under 10 years old.
- NO PERSONAL VEHICLES! All participants will be transported by van from the meeting site to the dig site.

Scan the QR code for more information and additional rules for participants.

WWW.DMR.ND.GOV/DMR/PALEONTOLOGY/FOSSIL-DIGS

Find more information on early registration opportunities at:

www.ndpaleofriends.org

NORTH DAKOTA LEADS THE NATION IN LANDSLIDE INVENTORY MAPPING

BY CHRISTOPHER MAIKE

Landslide inventory mapping has been an integral program at The North Dakota Geological Survey (NDGS) in recent years. The program began in 2003, by Ed Murphy, now the State Geologist. Mapping was initiated in the western portion of the state and utilized stereoscopic imagery. The landslide mapping program rekindled in 2017, primarily due to the increasing availability of LiDAR. The program has produced the most complete landslide dataset for state geological surveys nationwide. The United States Geological Survey (USGS) has publicly acknowledged that the mapping done by NDGS is essential to their efforts. First and foremost, the NDGS is conducting its work to benefit the citizens and operators within North Dakota. The mapping and understanding of landslides are essential to protecting critical infrastructure such as roadways, housing, well-pads, pipelines, and wind turbines (fig. 1). To date, the NDGS has mapped 76,126 landslides throughout the state of North Dakota.

WHAT IS A LANDSLIDE? WHAT TYPES OF LANDSLIDES DOES NORTH DAKOTA HAVE?

A landslide is the mass movement of rock, earth, or debris down a slope. Worldwide, landslides may be triggered by a variety of sources, such as precipitation events, groundwater impacts, forest fires, volcanic or seismic activity, fluvial erosion, or anthropogenic impacts. It can be very hard to predict the activity of landslides in North Dakota as many landslides are simply reactivations of ancestral slope failures that may have existed for hundreds of thousands of years.

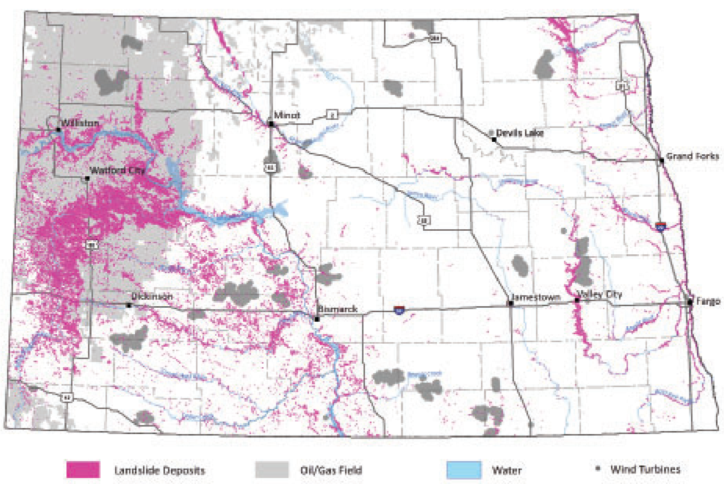


FIGURE 1.
Map depicting landslides and critical infrastructure locations throughout the State of North Dakota.

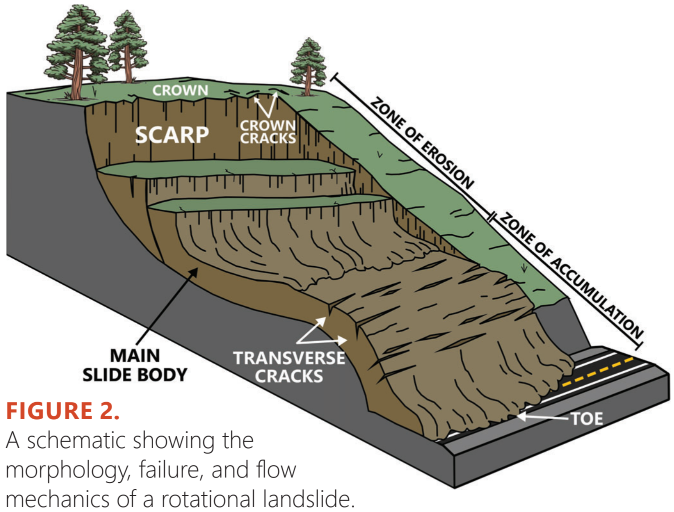
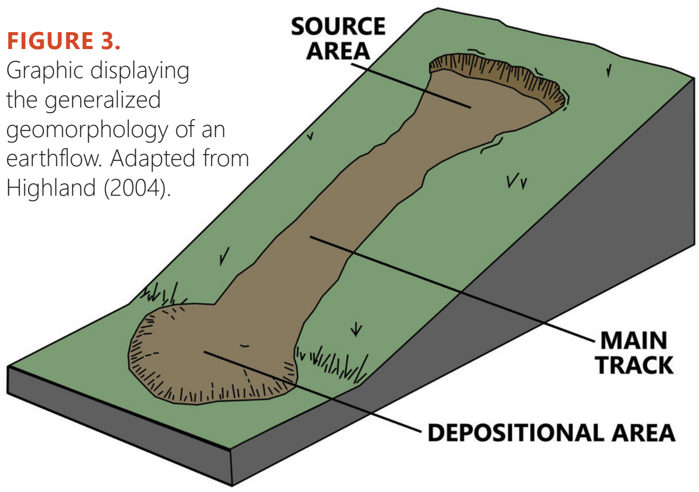


FIGURE 2.
A schematic showing the morphology, failure, and flow mechanics of a rotational landslide.
Modified from Bowman and Lund (2020) and Highland (2004).

There are as many as nine different types of landslides, however, rotational landslides are the most common in North Dakota (fig. 2). A rotational landslide is defined as, "a slide in which the surface of rupture is curved concavely upward, and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide" (USGS, 2023). These landslides can be activated and moved if a load is applied, or the support of the toe is removed. Another type of landslide observed throughout the state is an earth flow (fig. 3). An earth flow is more simplistic; when loose rock or soil becomes heavily saturated with water the soil and rock can become fluidized as the effects of gravity cause it to flow downslope. Earth flows are most seen in glacial meltwater trenches (eastern ND) and the Pembina Gorge (northeast ND) where the valley walls are comprised of clay-rich shales.

FIGURE 3.
Graphic displaying the generalized geomorphology of an earthflow. Adapted from Highland (2004).



WHAT DATASETS DOES THE NDGS USE TO MAP LANDSLIDES?

STEREOPAIR AERIAL PHOTOGRAPHS:

Internally, the NDGS boasts a complete USDA 1950s/1960s statewide 1:20,000 scale aerial photo collection with some additional photos dating back to the 1930s (fig. 4). These aerial photographs are collected from low-flying aircraft and have an overlap over one another and can be viewed by a stereoscope, allowing the user to be able to view and interpret the surface in three dimensions.

FIGURE 4.
NDGS geologists Levi Moxness (left) and Chris Maike (right) looking through historical aerial imagery in the archive room.

DIGITAL AERIAL PHOTOGRAPHS:

The National Agriculture Imagery Program (NAIP) is a program run by the United States Department of Agriculture that collects aerial photos annually. The program has been operational since 2002. In 2004, NAIP required the spatial resolution of photos to be one meter or better. This imagery is typically brought into software, such as ArcGIS Pro but is also commonly viewed in Google Earth. This is very useful as a user can remain in one location and toggle from year to year quite easily to observe any land changes. A great place to view geology data alongside many years of available NAIP Imagery is the NDGS Geologic Map Viewer, which can be found at: **https://www.dmr.nd.gov/dmr/ndgs/geologic-map-viewer**. For more information on the NDGS Geologic Map Viewer and the vast amount of data available, please see York (2024).

SATELLITE IMAGERY:

Satellites have been collecting useful imagery for decades. However, it was not until more recent years that it has become useful for mapping smaller landslides as resolution increased.

Massive landslides, typically those seen in mountainous regions and on the western coast of the United States, can be monitored with satellites such as Sentinel-1 using InSAR (Interferometric Synthetic Aperture Radar), a method using radar emitted from a satellite to monitor any land deformation. The very appealing rationale for using InSAR is that data is collected for an area approximately every two weeks, however, the downside is that data has a spatial resolution of around 300ft. Researchers at North Dakota State University are analyzing to see if this is a viable technique to monitor large landslide movement in North Dakota.

LiDAR:

Light Detection and Ranging, commonly referred to as "LiDAR" is a remote sensing technology that has drastically changed the way we map landslides in the last decade. LiDAR is used by scientists, surveyors, and engineers across a variety of disciplines to understand Earth's surface (Maike, 2016; 2021). The data for the statewide North Dakota LiDAR is collected by an aircraft with high-precision GPS equipment flying over the surface and emitting laser light pulses, the light reflects off the surface, and with the time it takes to reflect, a distance can be calculated. This results in a high precision x, y, z coordinates for each point collected. Hundreds of billions of LiDAR points have been collected throughout the State of North Dakota. After collecting these points, they are assembled into a point cloud (a dense array of data points with x, y, z coordinates attributed to them). From these points clouds, a digital elevation model (DEM) can be modeled which is a high precision representation of Earth's surface (fig. 5). Algorithms can be run to remove vegetation and allow for the creation of a bare earth DEM, the most common type of data used by NDGS geologists to identify landslides. This remote sensing technology is very useful statewide, and very helpful in densely forested areas, such as the Pembina Gorge.

North Dakota has a complete statewide dataset flown at Quality Level 3 (QL3), which has a DEM cell size of 1.5m-2m, and has nearly completed the second statewide acquisition of LiDAR at QL2 with 1m horizontal cell spacing (fig. 6). The collection of two statewide LiDAR datasets makes North Dakota one of the leaders in LiDAR collection and use. Credit for LiDAR data collection and data management can be given to the North Dakota Department of Water Resources.

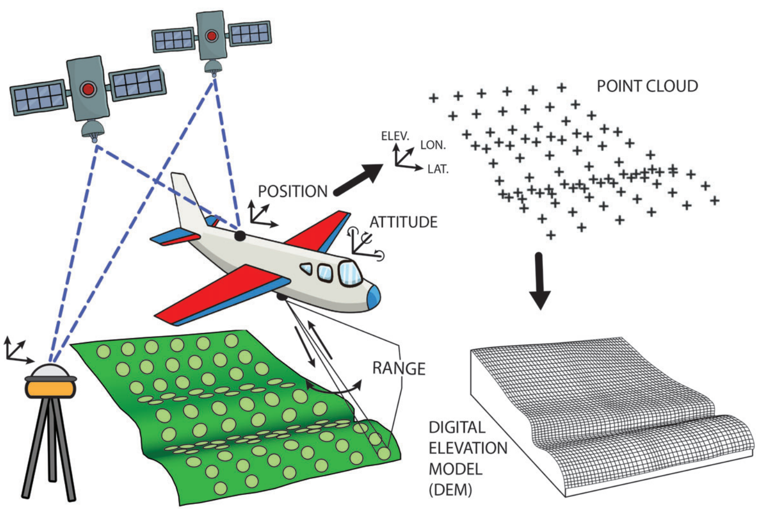


FIGURE 5.
A schematic displaying the collection and post-processing of LiDAR data. Adapted from https://historicmappingcongress.wordpress.com/wp-content/uploads/2012/06/lidar.jpg (Date retrieved October 4, 2024) and (Maike, 2016).

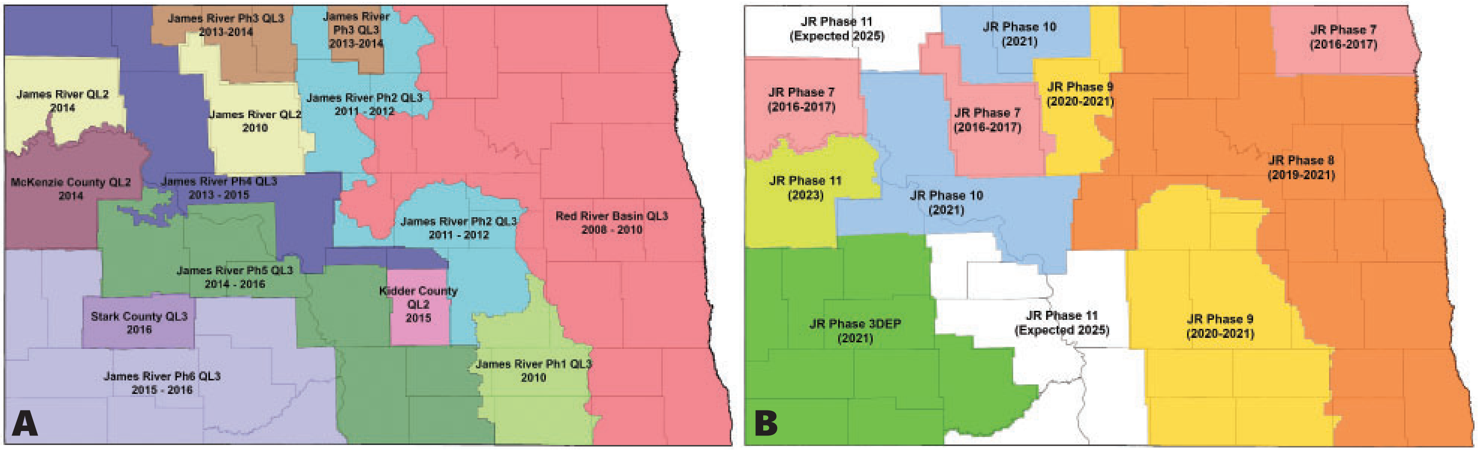


FIGURE 6.

(A) Date of acquisition and quality level of the first LiDAR pass and **(B)** The date of acquisition and quality level of the second LiDAR pass. On average, there are 5-10 years between collections. Map A is adapted from Maike (2021).

This is game-changing for landslide geologists, as it allows them to perform a technique called "LiDAR differencing," where multiple LiDAR datasets are brought into software, such as ArcGIS Pro, and the difference is calculated between the two (fig. 7). This method allows for any movement to be observed in the vertical (z) direction. Any negative z value could be interpreted as a net loss or erosion, whereas any positive z value could be interpreted as a net gain or deposition in the case of landslides (fig. 8). This method will account for any vertical change, such as river channel migration (fluvial erosion/deposition), mining, construction, and other anthropogenic activities, newly cut roads and trails, headward erosion in draws, and many other land disturbance impacts (Maike and Moxness, 2022). This is why it is of the utmost importance for geologists with years of experience in imagery interpretation to accurately delineate landslide movement using this technique.

The NDGS has been completing its mapping in phases, which relates to data used, technical availability, and detail of mapping performed:

PHASE 1: Data used: digital aerial photos, 1950s and 1960s aerial photographs viewed in stereopair and satellite imagery.

PHASE 2: Data used: digital aerial photos, 1950s and 1960s aerial photographs viewed in stereopair, satellite imagery, and LiDAR.

PHASE 3: Data used: digital aerial photos, 1950s and 1960s aerial photographs viewed in stereopair, satellite imagery, and multiple LiDAR datasets (LiDAR Differencing).

WHERE ARE LANDSLIDES OCCURRING IN NORTH DAKOTA AND WHY?

EASTERN NORTH DAKOTA

While eastern North Dakota is typically associated with having very flat terrain, that does not hinder it from having landslides impacting communities. The Pleistocene lake clays of the Sherack and Brenna Formations contain large amounts of swelling smectitic clays, resulting in instability and flow where they are not laterally supported. They can be especially weak along the banks of the Red River and can be easily mobilized during construction activities. In addition to landslides, these lake clays have resulted in localized foundation issues throughout the Red River Valley (Anderson, 2023).

Flooding during the last glaciation (Wisconsinan ~12,500 years ago) scoured deep channels in the eastern North Dakota surface, resulting in glacial meltwater trenches exposing the weak shales of the Pierre and Niobrara Formations below. Today, numerous landslides can be found in these meltwater trenches, such as the Sheyenne River Valley. This is highly evident in the Valley City area, where landslides are impacting I-94.

Despite its dense forest (dense for North Dakota), the Pembina Gorge is one of the most densely landslide-ridden areas of the state. Sitting beneath the tree cover is another large meltwater trench underlain by the Pierre shale, Cretaceous in age. This shale is very weak and due to the LiDAR differencing method being conducted by the NDGS, it is known that it

10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1
10	9	8	7	6	5	4	3	2	1

Raster 1

10	9	8	7	6	5	4	3	2	1
10	9	8	6	5	5	5	4	2	1
10	9	6	6	5	6	5	4	2	1
10	8	6	6	5	5	5	5	3	1
10	7	6	5	5	6	5	5	4	2
10	7	5	5	5	6	6	5	3	2
10	7	7	6	6	6	6	4	3	1
10	8	6	6	7	7	5	4	2	1
10	9	7	6	8	6	4	3	2	1
10	9	8	7	6	5	4	3	2	1

Raster 2

=

0	0	0	0	0	0	0	0	0	0
0	0	0	-1	-1	0	+1	+1	0	0
0	0	-2	-1	-1	+1	+1	+1	0	0
0	-1	-2	-1	-1	0	+1	+2	+1	0
0	-2	-2	-2	-1	+1	+1	+2	+2	+1
0	-2	-3	-2	-1	+1	+2	+2	+1	+1
0	-2	-1	-1	0	+1	+2	+1	+1	0
0	-1	-2	-1	+1	+2	+1	+1	0	0
0	0	-1	-1	+2	+1	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Differencing Raster Result

FIGURE 7.

Diagram showing raster 2 being subtracted from raster 1. This would be an example of the "z-value" and observing any change, as seen in the "Differencing Raster Result." This loosely portrays a landslide failure, with the red (net loss) being the scarp and downslope erosive movement and the green (net gain) being the downslope deposition and toe.

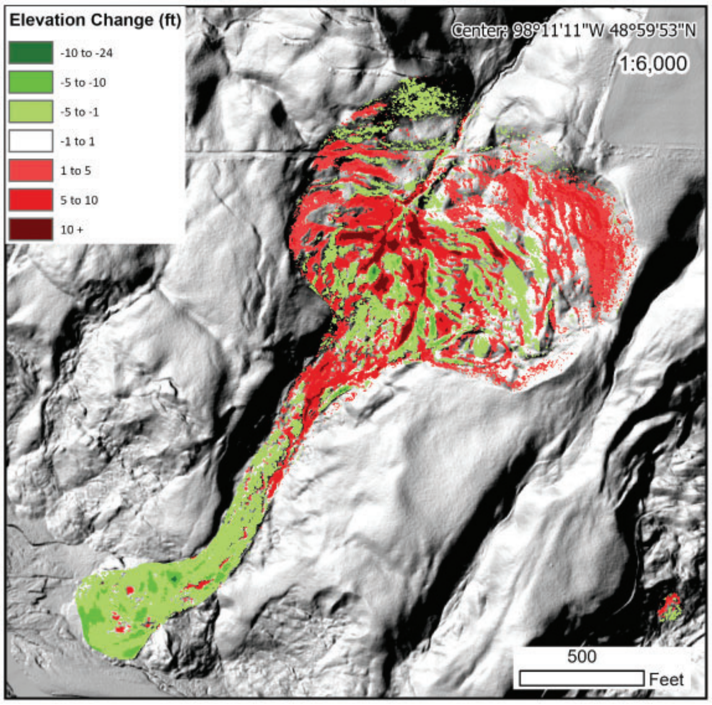


FIGURE 8.
Earthflow located in the Pembina Gorge in northeast North Dakota. Overlain on the LiDAR base is the resulting LiDAR differencing raster. LiDAR was collected here in 2008 and 2018, meaning anything in red is a net loss in the z-direction (erosion) and anything in green is a net gain in the z-direction (deposition).

is actively failing throughout the region. Luckily, there is no major interstate or infrastructure in this area, however, local roadways face issues from time to time, which may have implications for local tourism.

CENTRAL NORTH DAKOTA

While landslides in central North Dakota are much more limited, compared to the western and eastern parts of the state, they do still exist and cause impacts. Most are located in river valleys such as the Missouri River, Heart River, Souris River, Des Lacs River, and their tributaries. Some prominent landslides have occurred along the Missouri River, such as the River Road landslide in north Bismarck, which failed in December 2019 and has experienced reactivations of the slope, causing periodic closures of River Road (Moxness, 2020) (fig. 9). Also, there is a well-known landslide occurring near the University of Mary in south Bismarck. Both landslides occur along the steep ancestral valley walls of the Missouri River where the base of the slope was disturbed by road construction (River Road) or erosion from Apple Creek (University of Mary).

WESTERN NORTH DAKOTA

The defining rocks of western North Dakota which make up the picturesque badlands, from the Upper Cretaceous Fox Hills Formation up to the Miocene Arikaree Formation, compromise over 50% of the slope failures in the state (Moxness, 2022). These rocks consist of alternating beds of sandstone, claystone, mudstone, siltstone, and lignite.

FIGURE 9.
The River Road landslide in Bismarck, ND on December 22, 2019. UAS photo collected by NDGS geologist Levi Moxness.

Over time, the downcutting and erosion of the ancestral Little Missouri has caused slope instability throughout the badlands (fig. 10). This increased approximately 600,000 years ago when the ancestral Little Missouri was re-directed from south-north flowing to west-east flowing in the present-day northern portion of the badlands (Murphy, 2017), due to ice age base-level changes. This re-direction of water caused rapid erosion, which eventually resulted in tens of thousands of rotational landslides in southwestern McKenzie and northern Dunn County. As seen in Figure 1, these rotational landslides have a great potential to impact infrastructure in the region, such as roads, pipelines, and well-pads. Highways 22 and 85 have historically dealt with a great number of landslides through their history, including several re-routes and construction projects to mitigate landslide impacts and risk (fig. 11).

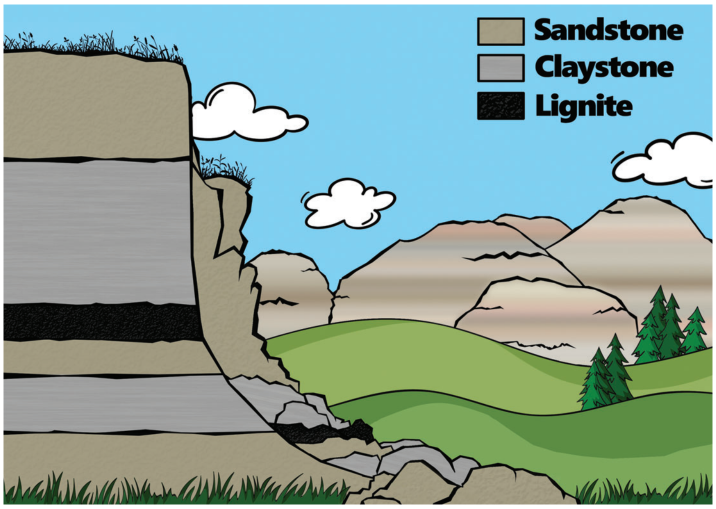


FIGURE 10.
Graphic illustrating the generalized North Dakota badlands lithologies within a rotational landslide.

UAS OPERATIONS

In addition to its standard inventory mapping, the NDGS also utilizes UAS technology to assist in monitoring known landslides. In 2017, NDGS geologists began using drone photography to complement their work, but dove deeper into the software capabilities to apply UAS work to landslides with software in 2019 (Maike and Moxness, 2020).

The monitoring of landslides has historically been done in cooperation with the North Dakota Department of Transportation Materials and Research Division. UAS operations are used on more site-specific projects. Using a technique called structure from motion, geologists can monitor movement from year to year. Structure from motion is a photogrammetric technique, where 2-D photos can be used to generate 3-D surfaces and models utilizing a software called Agisoft Metashape. For example, the NDGS has been monitoring the potential impact of landslides on a highway in western North Dakota. The NDGS has visited the site several times, and each time collected a dense array of photos.

Currently, the NDGS is using the DJI-Mavic 3 Enterprise RTK setup to collect orthoimagery for each site. This includes the DJI Mavic 3 Drone which boasts a 45-minute flight time per battery, a 4/3 CMOS sensor with 20 megapixels, an electronic and mechanical shutter, and an attached RTK Module, which allows the drone to connect to the D-RTK 2 Mobile Base Station. RTK stands for "real-time Kinematic," essentially the base station acquires high-precision satellite data and communicates it to the drone, making imagery collected very precise spatially (fig. 12). This results in centimeter-level accurate imagery. Pre-flight planning is essential to collect a consistent final product. Important pre-flight parameters include flight route, photo overlap percentage, terrain awareness, and drone height. A route or grid is created for each flight

FIGURE 11.
UAS photo displaying a landslide in the badlands of North Dakota. Note: the proximity of the landslide to Highway 22 (approximately 100 feet from the highway shoulder to the headscarp). UAS photo collected on October 8, 2019, by NDGS geologists Christopher Maike and Levi Moxness.

FIGURE 12.
Representative image of the DJI Drone and RTK Base Station that the NDGS utilizes. Image from https://www.aerotas.com/blog/dji-mavic-3-enterprise-rtk-review (Date retrieved October 4, 2024).

to capture the entire area. Photo overlap is important, typically the NDGS has 75-85% overlap between photos, which helps for the photogrammetric post-processing of images. The drone is typically flown around 200 feet above the surface, even in rugged terrain, using a setting called terrain follow. This results in a steady and consistent elevation of imagery acquisition (fig. 13). This allows for high-resolution horizontal data (approximately 2-3 cm) and a reasonable flight time, using a terrain-aware function, so that imagery is collected at a constant elevation above ground level. This is important, especially in the rugged badlands topography, for the post-processing of the data.

North Dakota geology is fascinating from the flat glacial Lake Agassiz plain of the eastern part of the state to the picturesque Badlands landscape of western North Dakota. Intermingled statewide throughout this varying geology and lithologies are landslides. The first thing to address a problem is knowing and acknowledging that you have one. With over 76,000 landslides documented statewide, the NDGS has tackled this challenge head-on. The NDGS goal is for the extensive dataset that has been amassed to mitigate landslide risk as development continues.

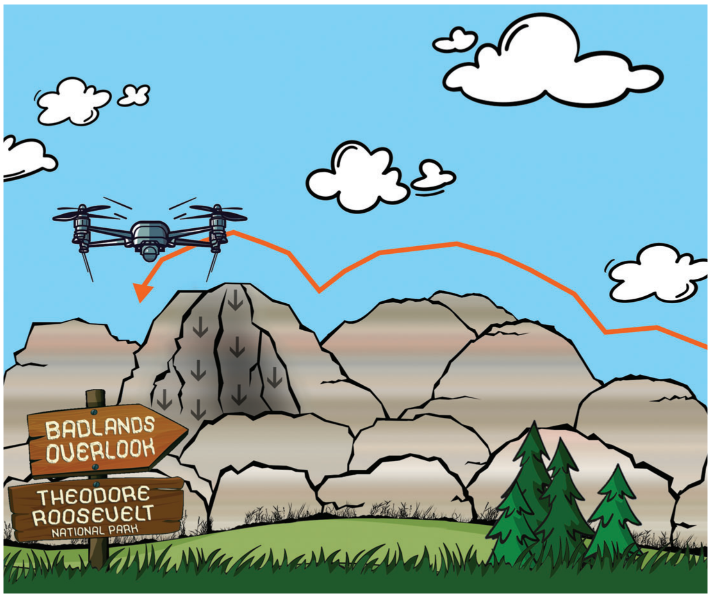


FIGURE 13.
Graphic displaying a drone flying at a consistent height above the ground surface using the terrain awareness function the NDGS uses in the field for its UAS operations.

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"The North Dakota Geological Survey is silently leading the way in landslide inventory mapping."
- Ben Mirus, Supervisory Research Geologist, USGS

A 10,000 FOOT* OVERVIEW
OF WHAT'S NEW(S) IN POTASH

BY NED W. KRUGER

PRODUCTION & PRICE

Early this year, the U.S. Geological Survey's National Minerals Information Center released commodity summaries containing statistics of domestic and world production for over 88 nonfuel mineral commodities, including potash. Potash refers to a potassium containing salt used chiefly as an agricultural fertilizer, but also having other chemical and industrial usages. The potash summary (Jasinski, 2024), reporting final statistics for 2022 and estimates for 2023, estimated a 4.6 percent drop in world potash production between the two years. Much of the drop in production was in Canada, producer of approximately one-third of the world's potash supply, where production declined by 1.6 million metric tons (fig. 1). This was partially due to a summer dock worker strike which led to temporary mine closures. Other influences on production have been more closely tied to recent price fluctuations in the commodity.

Revised historical spot price data indicates that potash began its most recent price surge in early 2021 and reached an all-time high of $1,200 per ton in May of 2022 before sharply receding in price in the latter half of the year, continuing a downward trend through 2023, and settling in 2024 (fig. 2). The price flux was largely reflective of supply insecurity from economic sanctions placed on Belarus and Russia in 2021, initially causing steep price increases. Other potash-producing nations, including Canada (fig. 1), revved up production in 2021 and 2022 to fill in expected sanction/conflict-related production declines. This led to over-supply as some Belarusian production continued to find its way to market by rail into China (Jasinski, 2024) and consumers reigned in their purchasing and reduced application rates for reasons both financial and due to weather conditions that disrupted field applications in the spring of 2022. Estimated domestic production declined in 2023 to 400,000 metric tons, the lowest it has been since 1940 according to historical statistics from the U.S. Geological Survey (2024). Production in the United States comes from mines in New Mexico and Utah.

POLITICS

As reported in the July 2022 edition of Geo News (Kruger, 2022), potash was removed from the U.S. Department of Interior's list of critical minerals in 2022. There have been efforts undertaken by the 118th Congress to return potash (and add phosphate) to the list of critical minerals. Doing so would underscore the national economic and security-based needs for domestic sources and resilient supply chains for potash (Mertz-Myers, 2024). House Resolution 4059 (2023) has been referred to the House Committee on Natural Resources and Senate Bill 3956 (2024) has been referred to the Senate Committee on Energy and Natural Resources. No additional actions have been taken on these measures at the time this article was written and as the 118th Congress approaches adjournment sine die.

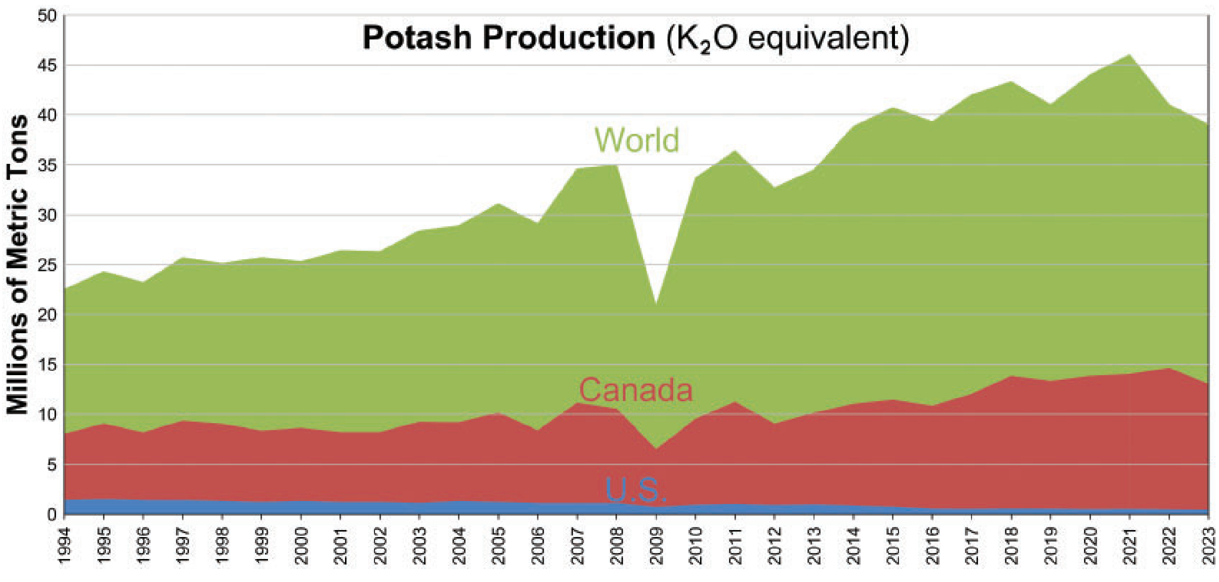

FIGURE 1. World, Canadian, and U.S. production of potash from 1994 through 2023. Source: U.S. Geological Survey Mineral Commodity Surveys.

**The approximate distance you would need to look down from your feet and into Earth to see the potash-containing Prairie Formation salts when standing in the town of Palermo, North Dakota.*

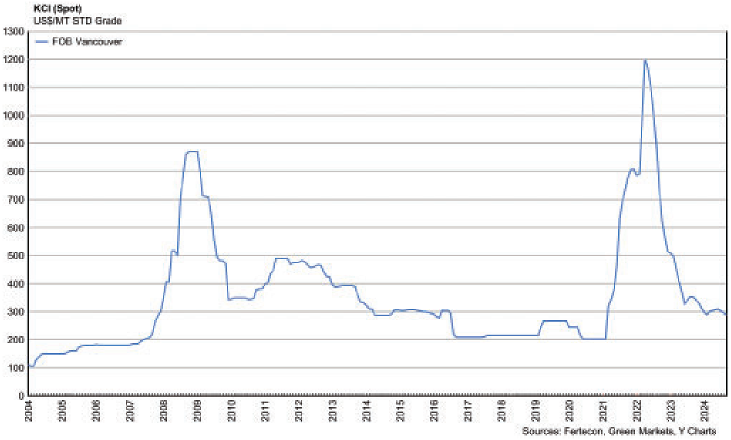

FIGURE 2.
Potash spot market prices from 2004 through September 2024. Sources: Fertecon, Green Markets, YCharts.

PUBLICATIONS

The North Dakota Geological Survey has completed seven 100K-scale map publications of the untapped resource of potash-containing intervals (members) of the Prairie Formation in northwestern North Dakota, with two more publications in progress (fig. 3). The available publications include a total of 32 isopach maps depicting member thicknesses and potassium oxide concentrations where they can be estimated by log-based calculations. Stratigraphically from top to bottom, the Prairie Formation potash members occurring in North Dakota are: White Lake, Mountrail, Patience Lake, Belle Plaine, White Bear, and Esterhazy. Canadian potash is mined from the Patience Lake, Belle Plaine, and Esterhazy members. In Canada, the White Bear potash is less prominent and is designated as a marker bed rather than a formation member. The Mountrail and White Lake Members were smaller, later-stage potash depositions limited to the southern locales of the Williston Basin in North Dakota. The potash members of the Prairie Formation in North Dakota account for most of the estimated total of 7 billion tons of potash resources in the United States (Jasinski, 2024).

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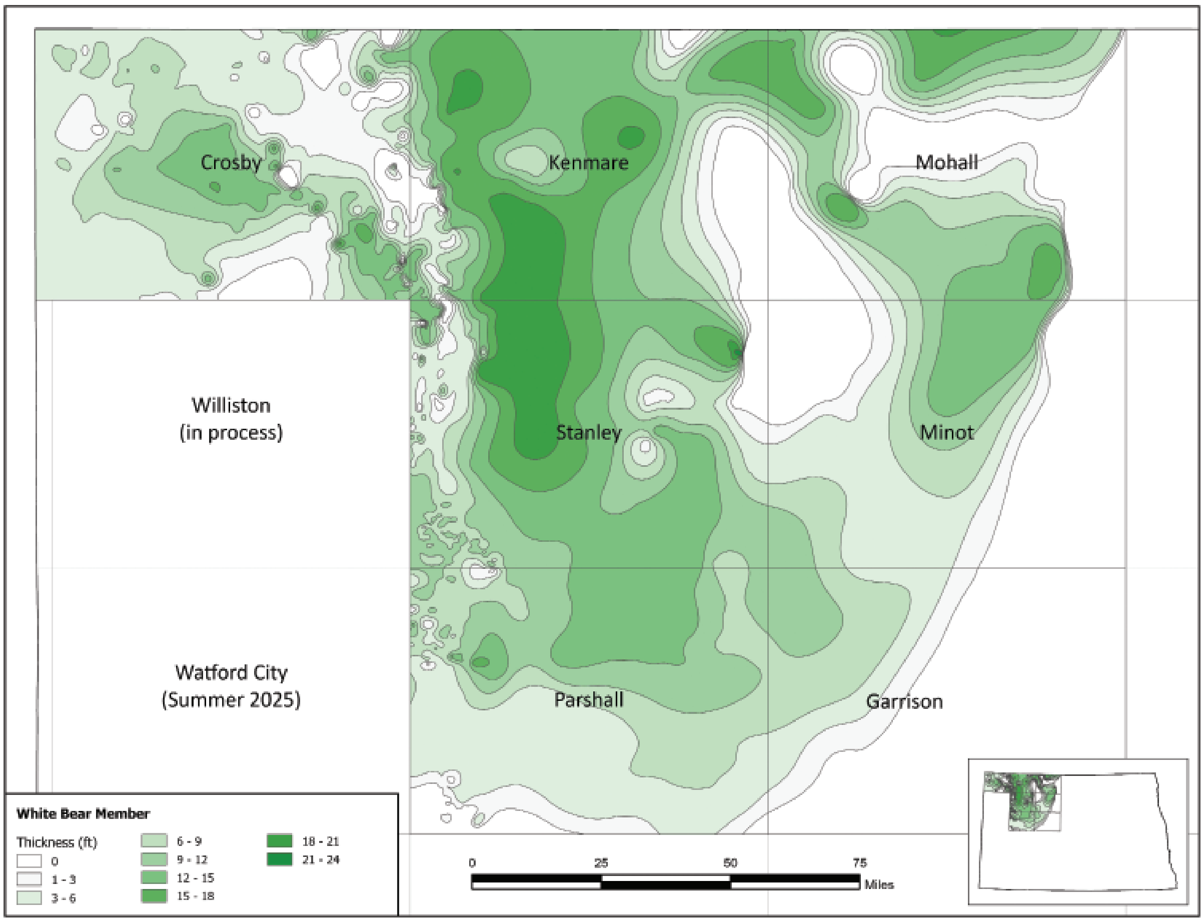

FIGURE 3.
Seven of nine 100K-scale map publications containing potash members of the Prairie Formation in the northwestern corner of North Dakota have been published by the NDGS. These sheets, identified by name in this figure, present thickness and potassium oxide estimates for the six potash-containing members of the Prairie Formation which occur in North Dakota. The White Bear Member is the most prominent of the potash members in the North Dakota portion of the Prairie Formation and is shown here as a compilation of maps included within publication numbers GI-209, GI-215, GI-247, GI-258, GI-268, GI-274, and GI-280.

X-RAY FLUORESCENCE:
UTILIZING A PORTABLE LABORATORY FOR CRITICAL MINERAL INVESTIGATION

BY ADAM CHUMLEY

For the last nine years, the North Dakota Geological Survey has collected numerous lignite coal samples across western North Dakota in an ongoing effort to investigate coals enriched in critical minerals, particularly rare earth elements (REE). REE are important in a variety of modern technologies including hybrid and electric vehicles, mobile phones, and power stations, among many others (Seredin and Dai, 2012). As such, a crucial component of this investigation is the geochemical composition of the coal. The standard method to obtain geochemical data is to send the coal collected from the field to a reputable laboratory that has the appropriate analytical equipment for geochemical analysis. However, doing so is costly and time consuming, particularly if a reliable method for predicting coal enrichment is not applied before selecting samples for laboratory analysis.

Fortunately, handheld devices that can detect element concentrations in geologic materials exist and are commonly used to detect approximate concentrations of elements in geologic materials when in the field or the office. The NDGS uses a portable handheld X-ray fluorescence unit (XRF, fig. 1), or pXRF, for a variety of tasks, including REE investigation. These pXRF units measure fluorescent X-rays from samples when those samples are hit with primary X-rays emitted from the device. These fluorescent X-rays are characteristic to specific elements on the periodic table and so are identifiable by the pXRF. These units are powerful tools for making informed decisions when sampling in the field. The first commercial XRF was introduced around 1948 (Bain et al., 1994), with the earliest portable versions becoming available in the 1960s (Karttunen et al., 1964). These portable XRF devices were non-intuitive and cumbersome, causing difficulty when operating them in the field (Rhodes and Rautala, 1983). It wasn't until 1994 that the first compact, single unit pXRF became available (Bauer, 2024). Since then, pXRF units have gone through many iterations, improving their analytical capabilities and establishing their utilitarian role in geochemical investigations. Though the pXRF unit is generally not as accurate as laboratory-sized analytical equipment and cannot detect as many elements as any of those instruments, it can detect yttrium. Yttrium is closely associated and often grouped with the REE, so if a coal is enriched in yttrium, then that coal is likely to be enriched in the REE as well. This is the method for quickly identifying REE enriched coals in the field that the NDGS has been using since purchasing a pXRF in 2021.

The pXRF was particularly useful for two recent REE projects. The first was a small project seeking to characterize an

FIGURE 1:
The Thermofisher Niton XL5 Plus pXRF in its case with accessories: **A)** analyzer, **B)** batteries, **C)** charge port, **D)** tripod, **E)** shielded sample chamber, and **F)** fan.

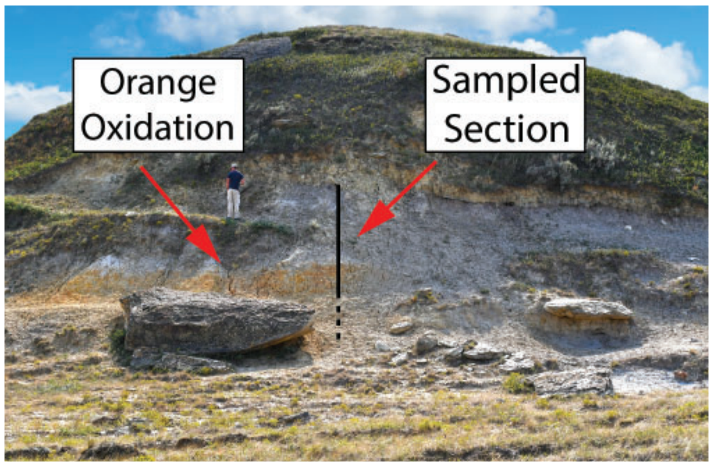

FIGURE 2:
Section of clay and coal within the Bear Den Member (geologist Levi Moxness pictured) sampled and analyzed with the pXRF. The white clay is commonly oxidized to orange, as it is here. The vertical line represents the sampled portion of the section and the dotted portion of the line represents where the section was dug further into the ground to collect coal samples not visible at the surface.

entire outcrop of coal and clay in the Bear Den Member of the Golden Valley Formation (fig. 2) to determine how and why the REE moved through the clays and became captured by the coal. Geologists collected 87 samples vertically through this section and ran over 400 geochemical analyses on those samples with the pXRF. The results reveal a high concentration of yttrium in the coal towards the bottom of the section below the clays, as expected, and depletion in potassium in the top of the clays above the coal (fig. 3). This was very informative to NDGS geologists, showing the clear contrast between the enriched coal and depleted white clay above it and indicating a period of weathering during which water may have leached the potassium and REE through or out of the clay. Coals below selectively uptake REE but not potassium. While the contrast in yttrium content between the coal and the clay has been seen in numerous samples collected by the NDGS over the last few years, most of those samples were collected at different locations around the state. This was the first time we were able to observe that relationship in a section at a single location, and quickly without high laboratory costs.

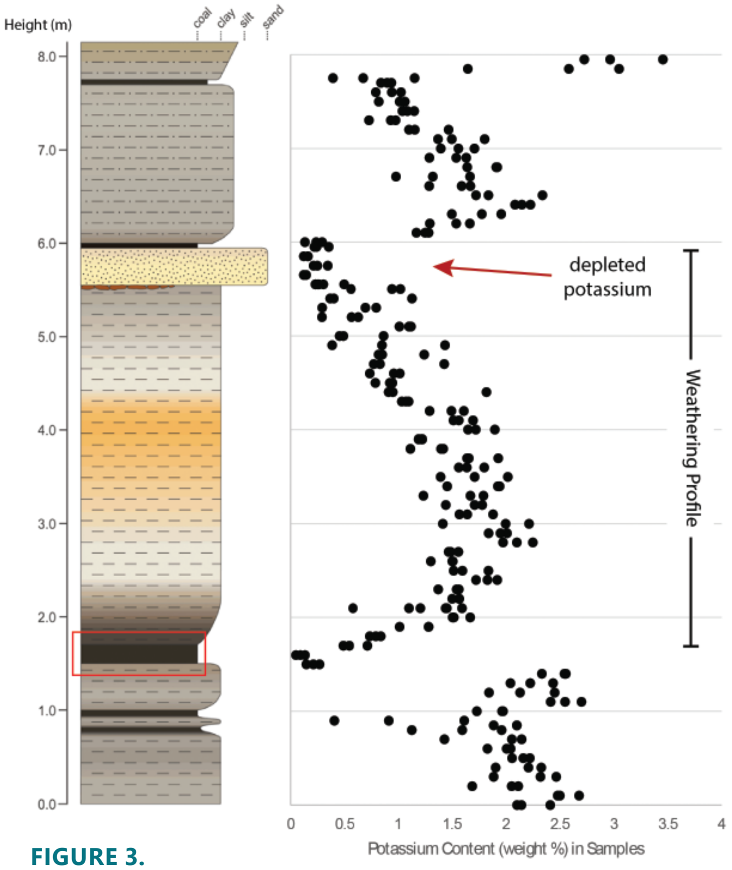

FIGURE 3.
A measured section (left) of the Bear Den Member in Stark County showing color and rock types, including the orange iron-staining in the white clay above the coal enriched in REE (red box). A graph of potassium content vs height of the samples (right) shows significant depletion at the top of the profile (red arrow), suggesting intense weathering and a possible source for the REE in the coal below.

FIGURE 4.
NDGS geologist, Adam Chumley, using the pXRF to analyze a coal core taken from within the Bear Den Member of the Golden Valley Formation in northern Hettinger County. State Geologist, Ed Murphy, (pictured in back) cuts the core for sampling.

Most recently, the NDGS undertook a three-week drilling project that sought to identify these enriched coals underground. After a location was drilled and cored, the pXRF was used to identify yttrium concentrations in coal within those cores at the drill sites (fig. 4). Several coals showed elevated yttrium concentrations (indicating high REE enrichment) beneath a depleted clay. Those samples were selected for full laboratory analyses by inductively coupled plasma mass spectrometry, to obtain accurate data on all the REE and other critical minerals. For more information regarding this drilling project, see Moxness, 2025.

The pXRF has been instrumental in making the process of sampling and obtaining geochemical data from North Dakota lignite and associated clays much more efficient and financially feasible. This was particularly true for the project investigating a single section of coal and clay, as it would not have been possible without the pXRF due to the high cost of laboratory analysis. As for the drilling project, the pXRF was crucial in constraining where and at what depth REE enrichment occurred and which samples should be sent for full laboratory analyses. The pXRF unit will continue to be an incredibly useful tool during future and ongoing geochemical investigations conducted by the NDGS, especially as the REE project moves forward.

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SKY HIGH SCIENCE:

Exploring Drone Sensor Technology in Geologic Studies

BY BENJAMIN C. YORK

CURRENT NDGS DRONE PROJECTS

The North Dakota Geological Survey (NDGS) has two drones in their inventory, the older Phantom 4 Pro, and the newer Mavic 3 Enterprise. Both of these drones changed the way NDGS geologists conduct physiographic field studies. The sensor housed on both drones is a standard camera that can take pictures and videos. In past newsletter articles, the authors described drone applications by the NDGS. If you are interested in reading an in-depth newsletter article about the types of drones and some case studies from North Dakota, see Anderson and Maike, 2017 and Maike, 2018a.

Drone work at the NDGS has primarily revolved around using aerial photography to capture oblique photographs and scouting/surveying hard-to-reach locations in the field. The oblique photographs taken by the drones have generally been of historic and active landslides. Many landslides have been recent enough that satellite imagery is not yet available, and if it is, the resolution is generally too poor to make small-scale models (Maike 2018b). The NDGS utilizes drones to produce on-demand three-dimensional digital surface models using photogrammetry. This converts multiple 2-D photos from a moving camera to generate 3-D landforms (Maike and Moxness, 2020). A recent landslide that the NDGS used photogrammetry on was the River Road landslide northwest of Bismarck, ND. This project showcased the detailed 3D surface that the drone and associated software could generate compared to LiDAR, or Light Detection and Ranging, and the power of repeat flights (model of the failure on December 22, 2019, and remediation on March 4, 2020) (Moxness, 2020). Drones can also be used to scout out terrain to validate locations to save on travel time, and even to view outcrops perched high up cliffsides. All this can be done with a standard RGB camera sensor.

TYPES OF SENSORS FOR DRONES

RGB CAMERAS

The first sensor on this list, and the most abundant is an RGB (Red/Green/Blue) camera, or just a standard camera like we have on our phones. This type of sensor is usually standard on most drones but still has quite a few implementations in science, notably photogrammetry which was mentioned earlier. Having on-demand imagery can be useful for landscape monitoring, including our landslide inventory work. The RGB sensor on both the NDGS drones, the Phantom 4 Pro and Mavic 3E, has a 20MP mechanical shutter camera. This sensor has sufficient resolution to analyze landslide-prone areas for further movement, or new movement.

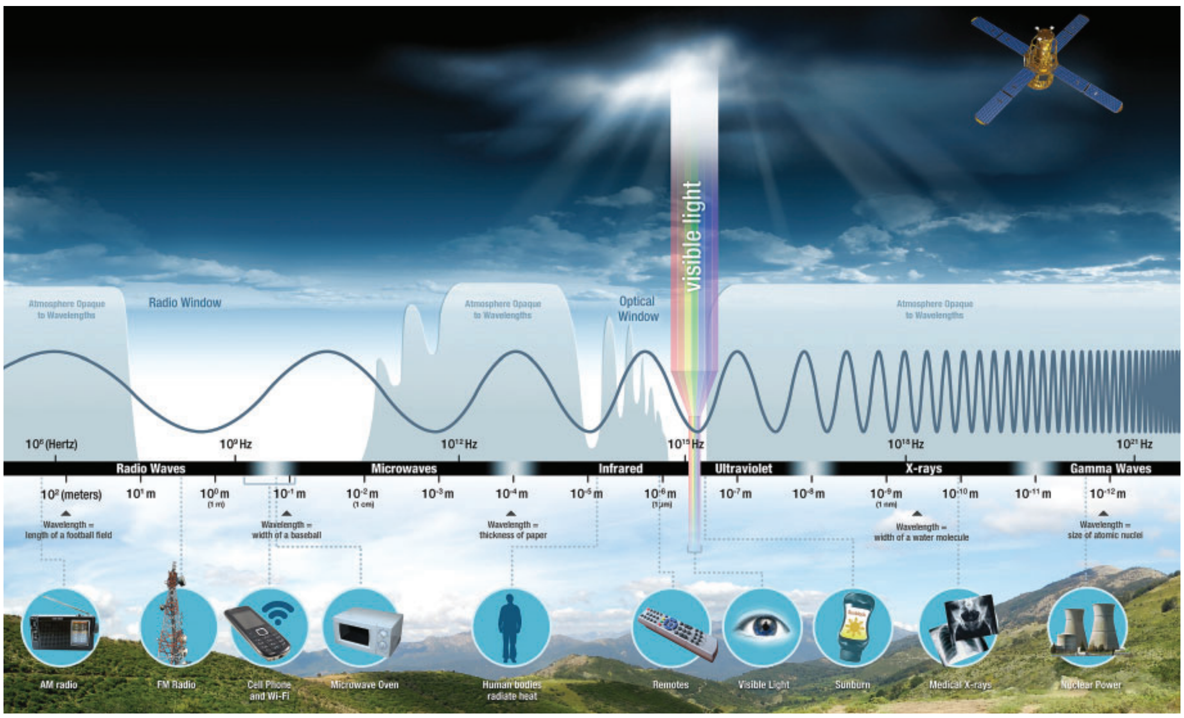

FIGURE 1.
"The electromagnetic spectrum includes energy from long wavelengths (radio waves), through visible light, all the way to short-wavelength X-rays and gamma waves" – NASA. All wavelengths, even visible light, are considered radiation. Longer wavelengths (radio and microwave) have lower energy and less radiation, and shorter wavelengths (X-rays and gamma) have higher energy and more radiation. (source: NASA, 2010)

This sensor is called RGB because of the three specific spectral bands (Red/Green/Blue) captured in the electromagnetic spectrum (fig. 1). The red band spans wavelengths around 600 to 700 nm (nanometers), green wavelengths around 500 to 600 nm, and blue wavelengths around 400 to 450 nm (USDA, 2017). These three bands comprise what we call "visible light" and are nearly identical to what our own eyes can process. As with our eyes, the sensors read wavelengths of light that are reflected off an object.

MULTISPECTRAL

While RGB only has a few bands, multispectral sensors can capture many more bands (wavelengths) that our eyes cannot see. The most common non-visible light wavelengths captured and used in geology are near-infrared (NIR) and short-wave infrared (SWIR). NIR has a wavelength of 800 to 900 nm and SWIR has a wavelength of 900 to 2,500 nm (USDA, 2017). The NIR band is sensitive to water and vegetative surface reflectance. Multispectral drone sensors can capture multiple bands at a time, with some sensors capturing 28 bands with wavelengths ranging from 440 to 1,640 nm. Using three bands at a time, researchers can mix and match different bands to create images that "highlight" specific features. An example of a common band combination used by the United States Geological Survey for their Landsat 8 multispectral satellite, would be combining bands 6 (SWIR), 5 (NIR), and 4 (Red) (fig. 2) used for vegetation analysis (USGS, 2021). Vegetation strongly reflects NIR, with higher reflectance indicating healthier vegetation. For geologic purposes, rocks and minerals reflect and absorb light differently. Transition metals (Iron, manganese, copper, nickel, and chromium) reflect visible and NIR, while hydroxyls (OH) and carbonates (CO3) reflect SWIR (Ghrefat et al., 2023).

While Landsat 8 is valuable for producing large datasets covering many square miles, the thing it lacks, and where drone sensors shine, is the resolution. Landsat 8 (fig. 2) band resolution ranges from 30 meters for most bands (and 15 meters for Band 9) to 100 meters for thermal infrared (covered later). Compare this to the modern multispectral sensors on drones that have resolutions in the centimeters, in addition to on-demand collection.

HYPERSPECTRAL

Seeing beyond our visible wavelengths into the infrared multispectral bands can show us details we would never be able to see with our own eyes, but using hyperspectral bands can fine-tune those details. While multispectral bands have ranges in the 10s to 100s of nanometers, hyperspectral bands can have ranges from 0.1 to 10s of nanometers. Having hundreds or thousands of bands allows researchers to find unique fingerprints of items they are studying.

Similar to the multispectral sensor housed on the Landsat 8 satellite, there are also hyperspectral sensors on other satellites, namely the NASA-launched satellite EO-1, the first of its kind. The EO-1 housed the Hyperion hyperspectral sensor, but the satellite was decommissioned in 2017. The space-based Hyperion sensor produced 30-meter resolution images with 242 bands (400-2500 nm). Unlike the global coverage of Landsat 8 images, EO-1 Hyperion images are only available on select locations and time stamps throughout the world. Since EO-1, other missions from other countries have launched satellites with their own hyperspectral sensors.

As with multispectral sensors, the advantage of drone-based sensors is greater resolution and more frequent flights. Hyperspectral drone sensors are usually more expensive than multispectral sensors, but the information they deliver reflects the price. Some readily accessible hyperspectral drone sensors have around 100 bands capturing a wavelength range of 500-1,000 nm. While a multispectral sensor with a few bands can identify groups of minerals and rocks in the field, a hyperspectral sensor with hundreds of bands can create more focused mineral identification.

A

LANDSAT 8		
BAND NAME	BANDWIDTH (µm)	RESOLUTION (m)
Band 1 Coastal	0.43 - 0.45	30
Band 2 Blue	0.45 - 0.51	30
Band 3 Green	0.53 - 0.59	30
Band 4 Red	0.64 - 0.67	30
Band 5 NIR	0.85 - 0.88	30
Band 6 SWIR 1	1.57 - 1.65	30
Band 7 SWIR 2	2.11 - 2.29	30
Band 8 Pan	0.50 - 0.68	15
Band 9 Cirrus	1.36 - 1.38	30
Band 10 TIRS 1	10.6 - 11.19	100
Band 11 TIRS 2	11.5 - 12.51	100

B

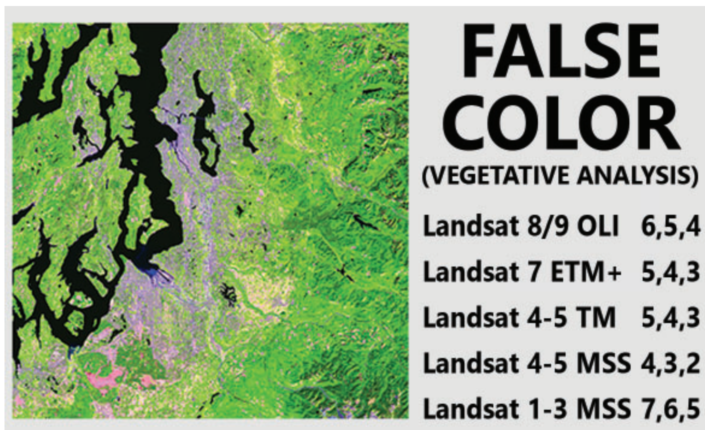

FIGURE 2.

A) Though not the most recent Landsat satellite (with Landsat 9 being launched in 2021), Landsat 8 has a much larger dataset that can be used for image comparison. Band wavelength assignments are subjective, but the multispectral bands on Landsat 8 fall within the accepted ranges of each type of light category. Most bands have a resolution of 30 meters, while thermal infrared is 100 meters (modified from Butler, 2013).
B) Example of a false color vegetative analysis using Landsat 8 bands 6/5/4. Healthier and denser vegetation is darker green while city infrastructure is purple (Image is Landsat 8 Path 46 Row 27 acquired August 23, 2020, of Seattle, WA, and surrounding area) (modified from USGS, 2021).

THERMAL

Taking a big leap along the spectral wavelength chart (fig. 1), we come to the thermal infrared (TIR) wavelengths along the electromagnetic spectrum, which range from 8,000 to 14,000 nm. While various multispectral bands such as RGB, NIR, and SWIR can readily detect transition metals and other groups such as hydroxyls and carbonates, those bands are not reliable in detecting quartz and feldspar minerals (Lyon, 1972). Here is where TIR becomes valuable in identifying these minerals.

Many people associate thermal infrared with reading levels of heat (by measuring electromagnetic radiation), which is accurate, but it can also be used to measure other characteristics exhibited by silicates. With silicates, the way the atoms are arranged can create a crystal structure that scatters TIR wavelengths, creating higher reflectance. This is in addition to the biggest reason scientists use TIR to identify silicates. The bond vibration between the silicon (Si) and oxygen (O) creates vibrations that resonate with infrared wavelengths and absorb and re-emit TIR creating higher reflection signals (Lyon, 1972).

There are a few satellites that house TIR sensors, including Landsat 7, 8, and 9, ASTER, ABHRR, MODIS, and Sentinel-3. Most of these satellite's sensors have TIR images around 100m resolutions (except the one TIR band Landsat 7 which is 60m). ASTER and Landsat 8 have the most coverage for imagery, but the poor resolution makes any small-scale field work difficult. Once again, here is where drone-based TIR sensors shine with their ability to fly closer to the ground and capture higher-resolution images.

LiDAR

Now we move away from sensors that capture the reflectance of wavelengths along the electromagnetic spectrum, to recording distance using the time it takes for a laser pulse to travel. LiDAR sensors emit hundreds of thousands of NIR laser pulses a second and record how long it takes for that pulse to bounce back from a surface (Fernandez-Diaz et al., 2014 and Maike, 2016). North Dakota currently has excellent LiDAR coverage, sometimes two datasets, both with resolutions of a few meters. Having high-resolution LiDAR has revolutionized landslide mapping at the NDGS and will continue to play a crucial role in future geological mapping. While the current North Dakota LiDAR set is a modern marvel and great for capturing a landscape on the move, there is one thing that it lacks, frequent repeat coverage. Drone-based LiDAR sensors can address that problem.

LiDAR is unique in that it can send multiple laser pulses and record multiple returns essentially creating a separate dataset for every return (fig. 3). The first return typically represents the first object the laser hits, which is typically the tree canopy or building roofs. The last return is the laser pulse that penetrated the tree canopy and other foliage and returned giving us "bare earth" data points. The bare earth data points are used to create digital elevation maps (DEM). With landscape mapping, especially landslides, tree cover on aerial photos often hides landslides and

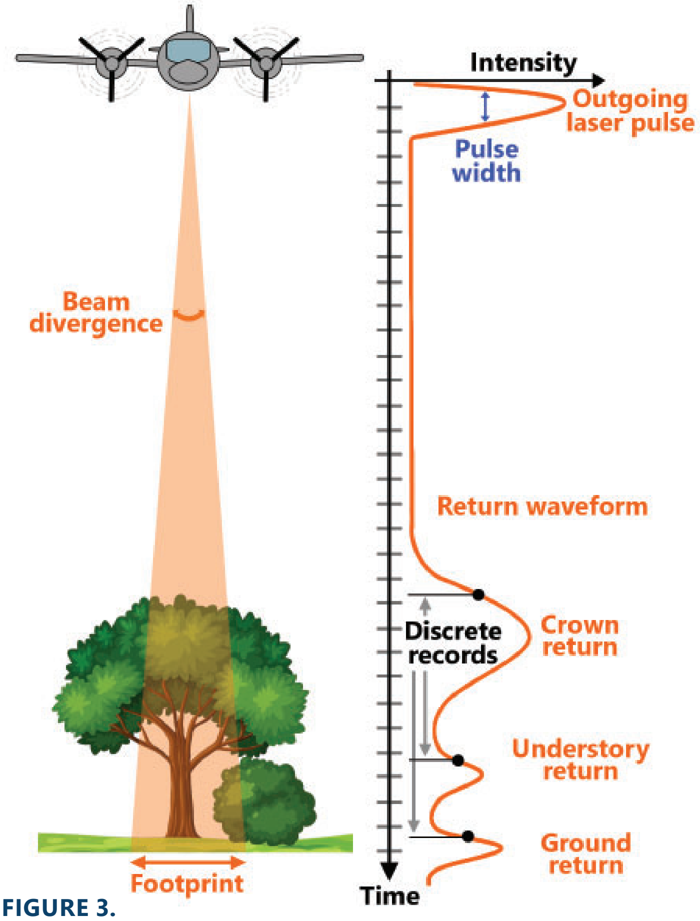

FIGURE 3.
Each pulse from the LiDAR system sends out multiple signals in a waveform curve, and each return can be classified as a different type of surface with the first return representing the object closest to the LiDAR system. This figure is an example of multiple returns in a wooded environment. (modified from Fernandez-Diaz et al., 2014)

LiDAR is needed to delineate them. The NDGS has waited nearly 10 years to get second flights in parts of the state giving us a 1-meter LiDAR dataset to see if there are active landslides. With drone-based LiDAR we would be able to get on-demand LiDAR and potentially capture a landslide the day before and after a substantial slope failure (Maike, 2018a). We can already create a pseudo LiDAR dataset using photogrammetry, but it cannot produce a bare earth dataset without tree cover. This sensor would most directly enhance ongoing NDGS projects.

GROUND PENETRATING RADAR

GPR (Ground Penetrating Radar) is like LiDAR in that it uses different wavelengths and frequencies to make measurements. While LiDAR uses NIR (about 900nm) light wavelengths, GPR uses 1mm to 1-meter microwaves. With GPR, it is important to note that the frequency of the energy is just as important as the wavelength. Higher frequency provides better resolution, but lower ground penetration depth, while lower frequency results in greater ground penetration depth. Most drone-based GPR sensors are around 500 MHz and can penetrate about 4 meters into the soil while being able to detect objects as small as 10cm. At 600 MHz, GPR can penetrate to 6 meters or even 10 meters under ideal circumstances. Like LiDAR, GPR also records the time it takes for the signal to be reflected and returned. The signal travels through materials differently based on permittivity, or how much electric field is reduced within a material compared to a vacuum. The signal sent from the GPR reflects off wet clays and silts very differently than through dry sands and soils. To see deeper rock formations, possibly up to 10 meters, the sensor would use a lower frequency to get a general scan of the area. Using a combination of different frequencies, the sensor can detect multiple rock formations at different depths (fig. 4).

GRAVIMETERS

A lesser-used sensor, which is available for drones and small UAVs due to recent technological advancements, is a gravimeter. The gravimeter measures gravitational field variations which indicates density changes in Earth's crust. As the drone flies over the terrain, the gravimeter detects minute changes in gravitational acceleration. Different rock types will have different readings when a drone-based gravimeter flies over them. For example, igneous rocks tend to have higher gravitational pull compared to sedimentary rocks like sandstone. This is reflected in the mineral composition, with rocks with high concentrations of heavy minerals like magnetite will have stronger gravitational effects. Gravimeters can also be used to detect anomalies like faults and voids such as large caverns. Only with recent technology are gravimeters even an option for drones, so results for gravimeters on small-scale projects are still underway.

MAGNETOMETERS

The last sensor covered is the drone-based magnetometer, which measures variations in Earth's magnetic field. In some ways a gravimeter and magnetometer will show overlapping results, as a gravimeter will have stronger gravitational effects for heavy minerals (which may be magnetic), and a magnetometer will record the magnetic anomalies associated with magnetic minerals such as iron and nickel. For a drone-based magnetometer, the

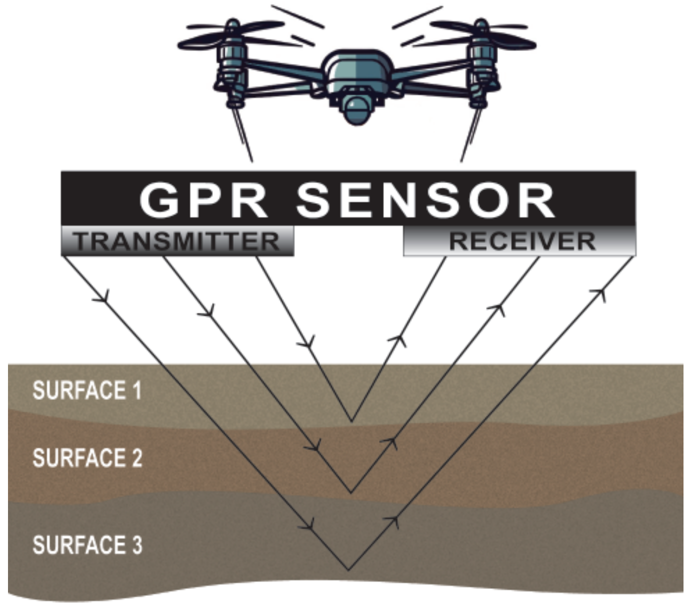

FIGURE 4.
Ground penetrating radar works similarly to LiDAR in that the transmitter sends out multiple signals with each penetrating a different depth. This simplified figure shows that a GPR sensor can detect multiple subsurface layers using a single sensor, though in a drone sensor, the transmitter and receiver are packaged together for drone accessibility.

applications tend to be small-scale, like locating small ore deposits or archeological artifacts, and are generally not used for large-scale projects.

FINAL THOUGHTS

Geologic application of drone-based sensors is still a developing field, and sensors are getting smaller and better. While there might only be a few sensors applicable to North Dakota projects currently, the longer the technology is available for industry use, the more that new methods will be introduced. Here at the NDGS we always keep an eye out for new geology-related technology and are researching new ways to use them in the field.

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SHALLOW SALT CANDIDATES FOR UNDERGROUND STORAGE IN NORTH DAKOTA

BY STEVE CHITTICK

Maps of the shallow-bedded salts of the Williston Basin in North Dakota have recently been updated by the North Dakota Geological Survey. These maps have been utilized by various salt cavern characterization studies (e.g. Smith 2023). The shallow-bedded salts are currently being considered as candidates for solution caverns. Solution caverns are created for storage by dissolving the salt with fresh water to create a void. A variety of products can be stored in the solution caverns including petroleum feedstock, hydrogen, helium, and compressed air. North Dakota has three main shallow salts with the capacity to create salt caverns with bedded salt thicknesses up to 190 feet.

Ideal candidates will be shallower salts due to geomechanical issues. A minimum thickness for salt cavern creation is between approximately fifty and sixty feet (Steven Smith, EERC 'personal communication' December 12th, 2023). The three main shallow salts in North Dakota, in order of increasing depth, are: the Jurassic Dunham salt, the Triassic Pine salt, and the Permian Opeche salt (fig. 1). The Opeche salts were initially dismissed as a candidate for salt cavern storage due to reports of unfavorable salt types. A nearly 300-foot core from the Romanyshyn 2-33-4B (NDIC# 8927, API# 33007007480000) in Little Knife field, Billings County, North Dakota indicates that the thick Opeche salts are favorable halite (from X-ray fluorescence data analysis: in progress) and are potentially a good candidate to create salt storage caverns.

The thickest of the three bedded salts is the Dunham salt with a maximum thickness of 190 feet (Stolldorf, 2021). Although this salt is the thickest, it is also the most inconsistent in areal extent. It can be a good candidate in specific areas, such as along the US 85 corridor from Williston to Belfield where its thickness is most consistent (see fig. 2, left top).

The next thickest salt is the Pine Salt with a maximum thickness of 164 feet (Stolldorf, 2022). It is more consistent in areal extent than the Dunham salt, especially in the southwestern corner of the state (see fig. 2, left center).

The Opeche Formation contains two thick salt units: the shallower, thicker Opeche A salt (maximum thickness 123 feet, Chittick 2024a) and the deeper, thinner Opeche B. The maximum thickness of the Opeche B salt is 58 feet (Chittick, 2024b), marginal for salt cavern creation and is not considered further here. The Opeche A salt is the most consistent in areal extent of the three salts and is concentrated in the west-central part of the state (see fig. 2, left bottom). The overlap of the areas where these salts are ≥60 feet is shown in figure 2, far right. The mapping presented has used a cutoff of 60 feet as the minimum thickness for salt cavern creation.

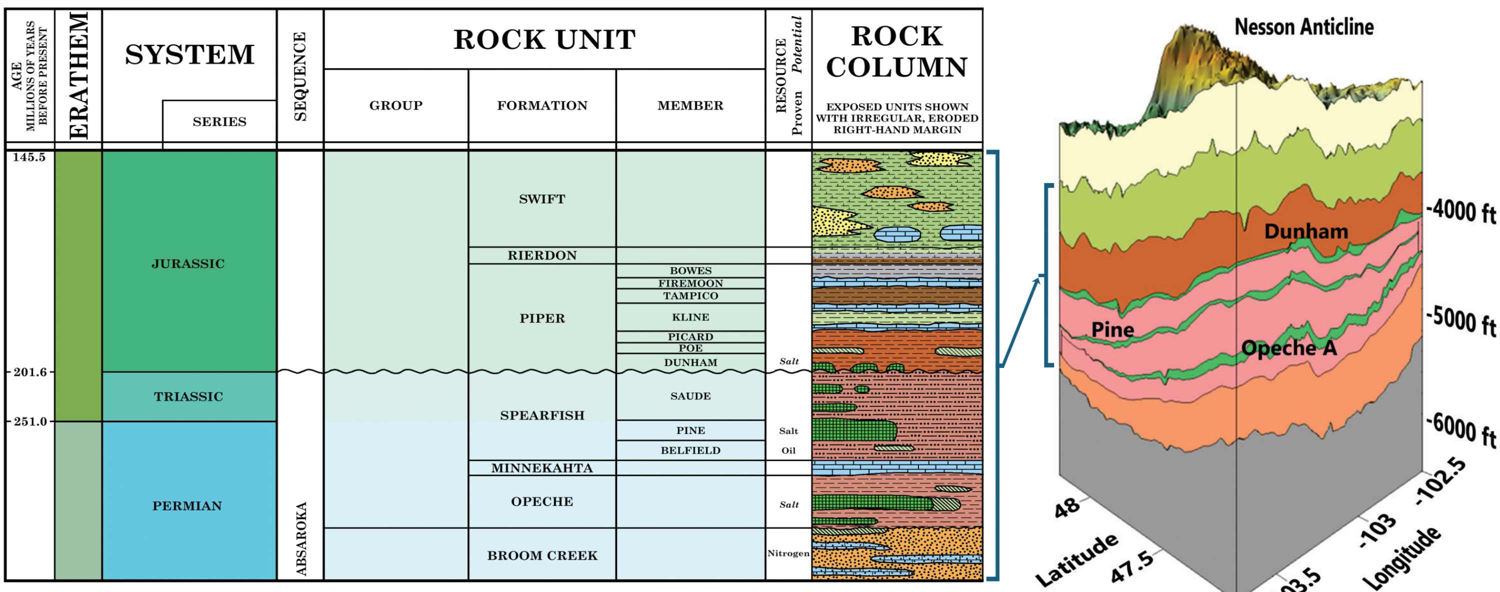

FIGURE 1.

Stratigraphic column of the intervals containing the major shallow salts of the Williston Basin in North Dakota (Murphy et al., 2009). Salts are represented by the green cross hatch pattern in the rock column on the left and in green in the 3-D block diagram of the central basin on the right.

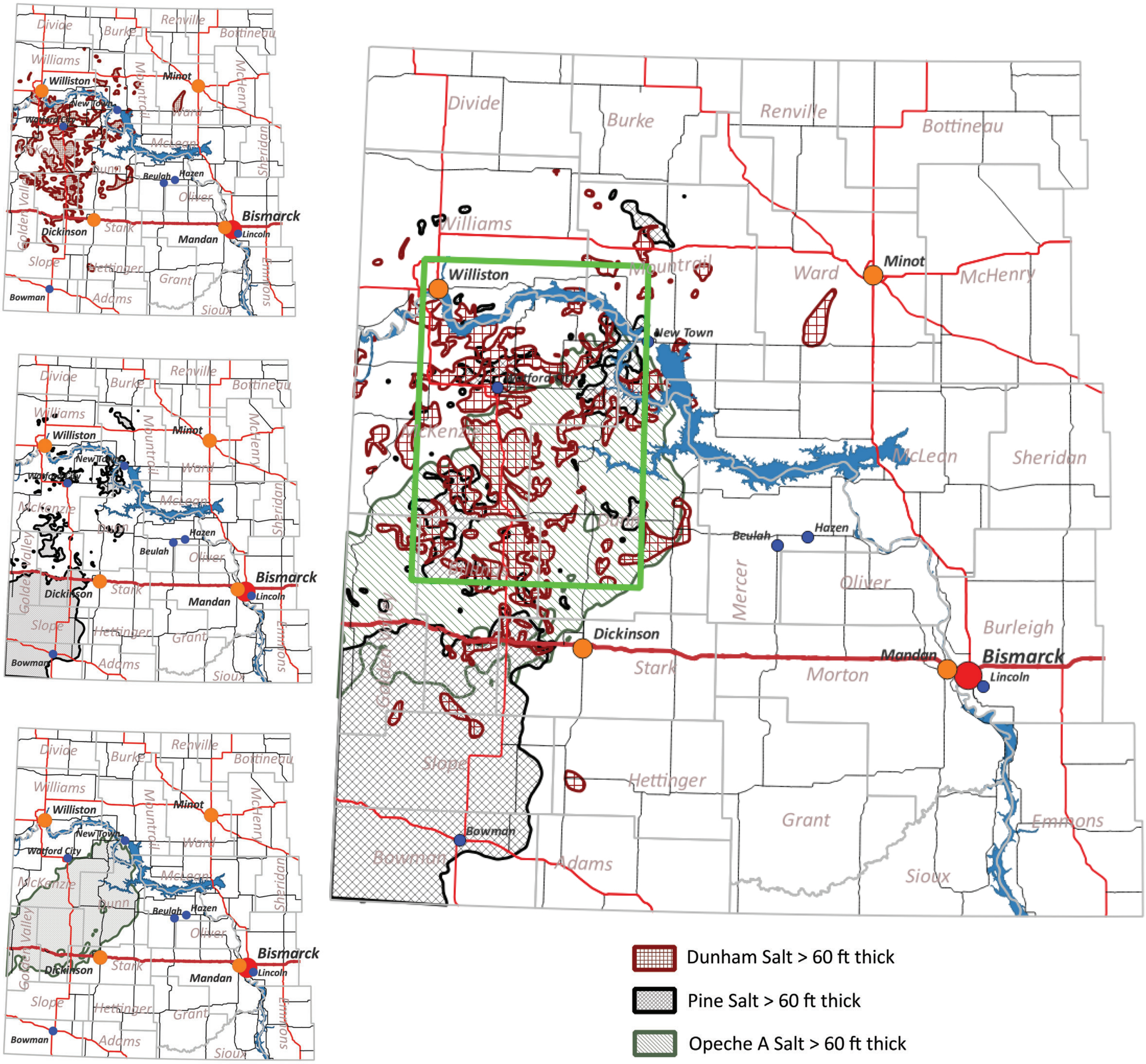

FIGURE 2.
Maps of the individual shallow salts greater than 60 feet (left) and a map of the combined Dunham, Pine, and Opeche A salts with thicknesses greater than 60 feet (right). The green rectangle in the image on the right outlines the footprint of the 3D block diagram in figure 1.

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MUDSTONES IN THE CANNONBALL FORMATION EXPOSED ALONG THE HEART RIVER SOUTH OF MANDAN.

THE CANNONBALL FORMATION IN THE BISMARCK-MANDAN AREA: POTENTIAL GEOLOGIC INSTABILITY IN SHALLOW GEOLOGIC UNITS

BY FRED J. ANDERSON

Geologists use the term Formation (with a capital F) to speak of packages of rocks, much like pages in a book, with layer upon layer with distinct similarities in rock properties that are found over a large area. Some of these formations contain sediments that can be problematic for commercial and residential property development.

For example, in the Bismarck-Mandan area the Cannonball Formation is comprised of sandstone and mudstone of marine (oceanic) origin that represents the deposits from the last sea (i.e. the Cannonball Sea) to cover this area in early Paleocene time (figs. 1-2) (Murphy et al., 2009). On the surface, the formation commonly consists of interbedded yellow-brown, yellow-gray, and olive-gray sandstone, siltstones, shales, and lenticular limestones. A well-indurated sandstone is often found capping the unit where it outcrops on isolated hills in the area (fig. 3). In the shallow subsurface it contains interbedded olive, greenish-black and brownish-gray claystone, sandstones, siltstones, and limestone. The claystones and siltstones are non-calcareous, with carbonaceous material and flakes of mica.

FIGURE 1.

Paleoenvironment of the Cannonball Sea in North Dakota in early Paleocene time (~60 Ma). Sharks, rays, and ratfish would have been found in these waters along with crocodiles, birds, and small mammals on land (Person, 2024).

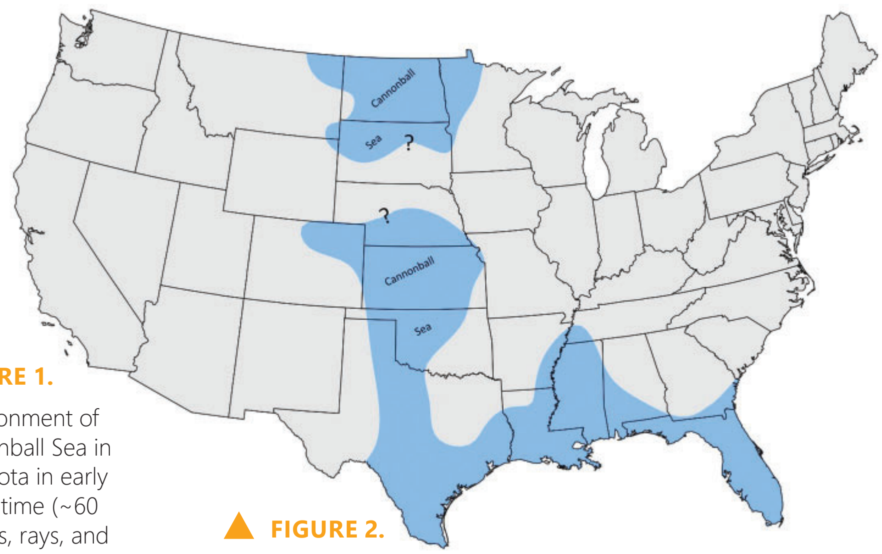

FIGURE 2.

The Cannonball Sea covered nearly all of North Dakota during the early Paleocene (~60 Ma) and deposited layers of sandstones, mudstones, and claystones which make up the Cannonball Formation. It is exposed in outcrops across central and western North Dakota (modified from Slaterry and others, 2013).

FIGURE 3.
The Cannonball Formation, a marine sandstone and mudstone deposited during early Paleocene time covered the Bismarck-Mandan area and represents the last sea to cover the region. Outcrops are commonly found at the tops of hills like this one just west of Mandan. Well-cemented (indurated) sandstone ledges (dark brown) capping poorly cemented (gray) sandstone are common in these outcrops.

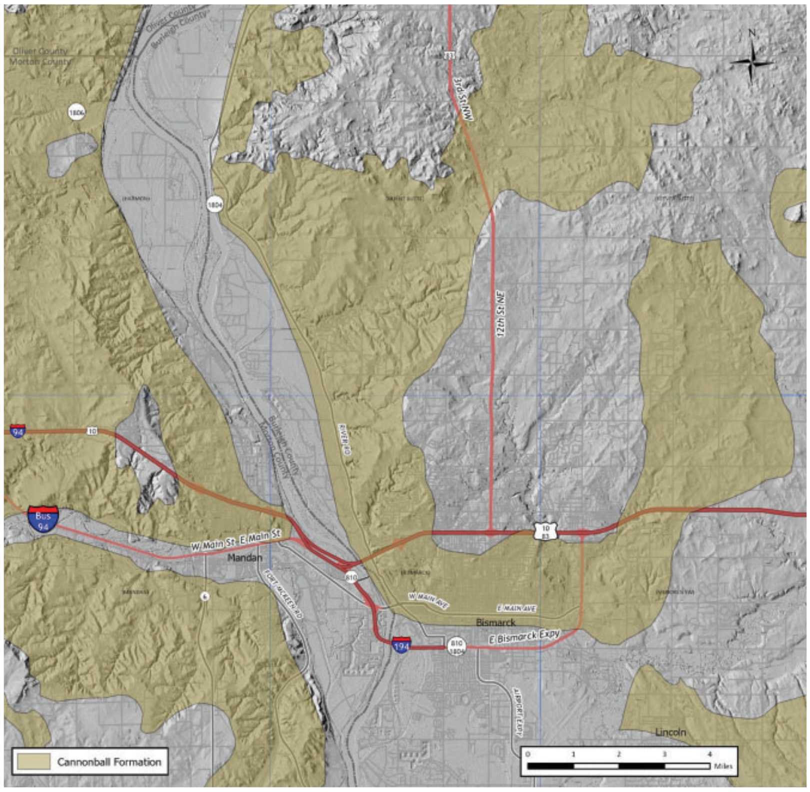

FIGURE 4.
The Cannonball Formation (shaded in tan) is exposed at the land surface or buried just beneath a shallow layer of glacial sediments throughout the northern Bismarck-Mandan area. Future geologic investigations to better characterize this unit are planned.

Fossils from the Cannonball Formation are consistent with its shallow marine origin and include crabs, shark teeth, and petrified wood fragments.

The Cannonball Formation is exposed at the surface or is present just below a thin layer of glacial cover in the Bismarck-Mandan area (Murphy, 2004) and is commonly encountered in numerous residential developments, particularly in north Bismarck (fig. 4). Problems with basements and shallow foundations are known in this area and have required costly remedial measures and repairs to both residential and commercial properties. The problem occurs primarily within the mudstones and thinly interbedded sandstone/siltstones (fig. 5) where expansion and contraction can occur within the clays. The clays within the mudstones are mixed compositionally and can contain swelling clays called smectites. When dry conditions are present these clays can shrink or contract (i.e. desiccate) and cause fractures to open and provide increased pore space where, when conditions change from dry to wet, can fill and rehydrate the clays causing expansion that exerts pressure on surrounding foundations, and basement walls (fig. 6).

Swelling clays with high concentrations of montmorillonite or smectite clay minerals can undergo as much as a 30% change in volume when going from dry to wet or wet to dry states. The smectites draw water molecules into their interlayered clay mineral structure causing them to expand. Conversely, when these same clays dry out the resulting contraction can cause deep cracks and fractures within the overall rock mass.

Identifying where the Cannonball Formation contains these problematic mudstones in the Bismarck-Mandan area would be the focus of future engineering geologic drilling investigations (fig. 7). Materials testing can be performed on samples collected from discrete intervals providing a detailed characterization of lithology, geochemistry, and geotechnical properties (fig. 8). Clay mineralogy analysis and shrink/swell potentials can be evaluated in the laboratory as well as in situ (i.e. in place).

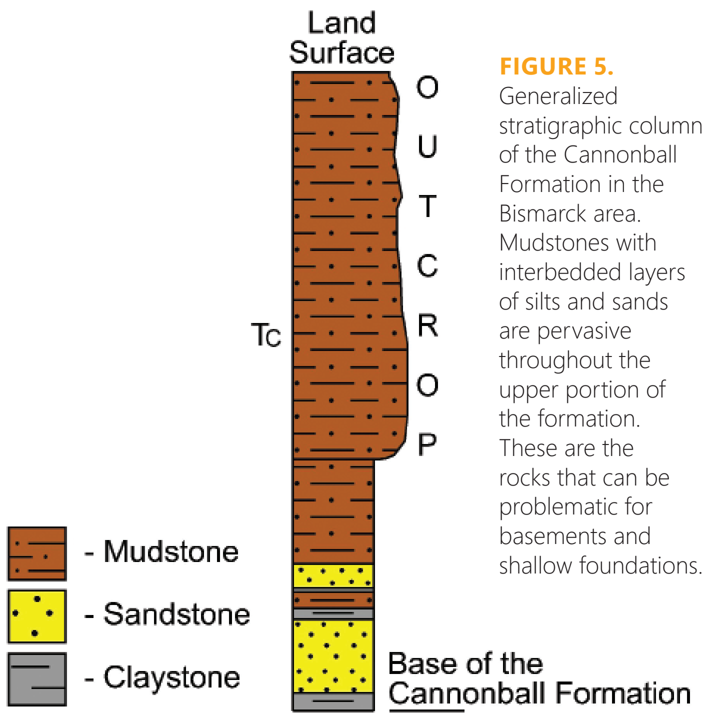

FIGURE 5.
Generalized stratigraphic column of the Cannonball Formation in the Bismarck area. Mudstones with interbedded layers of silts and sands are pervasive throughout the upper portion of the formation. These are the rocks that can be problematic for basements and shallow foundations.

FIGURE 6.
Layered and fractured mudstones of the Cannonball Formation exposed in an excavation for a home in north Bismarck. Fractured bedrock like this can be a conduit for shallow groundwater accumulation and flow which can exacerbate problematic foundations conditions created by swelling clays within these mudstones.

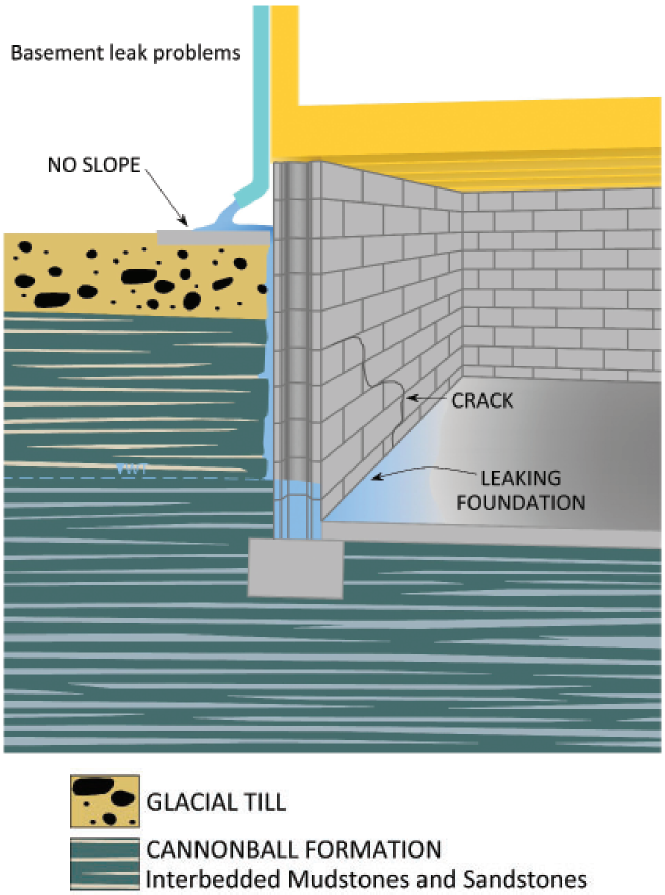

FIGURE 7.
Relationship of basement foundations to adjacent and underlying bedrock of the Cannonball Formation in north Bismarck. When the areas around a basement or shallow foundation are not sloped so that water can flow away from the house, water can seep down along the outside portion of basement walls allowing layered clay sediments to saturate and expand putting pressure on buried structures. Similar effects can be seen during the winter months with frost penetration and freezing and expansion of shallow groundwater saturated soils.

FIGURE 8.
The Cannonball Formation contains mudstones with interbedded siltstones and sandstones. These interbedded layers of dark gray claystone and gray-brown siltstone and sandstone contain varying percentages of swelling clays and can be problematic for shallow foundations and basements in some areas in north Bismarck with changes in moisture conditions (camera lens cap is 2.5-in. in diameter for scale).

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REPORTS OF INVESTIGATION

Nesheim, T.O., and Starns, E.C., 2024, Middle Three Forks Development in the Bakken-Three Forks Petroleum System, Rate Acceleration or Resource Addition?: North Dakota Geological Survey Report of Investigation No. 135, 24 p.

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OUTSIDE PUBLICATIONS

Person, J.J., Boyd, C.A., and Barnes, B., 2024, 25 Years of Public Fossil Digs at the North Dakota Geological Survey, Society of Vertebrate Paleontology, Abstracts, p. 438.

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