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FEATURES

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ON THE COVER:
A 58-million-year-old fossilized tree stump (perhaps dawn redwood or bald cypress) weathering out of rocks in the Sentinel Butte Formation a few miles north of the North Unit of the Theodore Roosevelt National Park in McKenzie County. The Sentinel Butte ash/bentonite (blue bed) is present at the top of the ridge in the background. Photo by Ed Murphy.

CRITICAL MINERALS

BELOW NORTH DAKOTA'S OLDEST LANDSCAPES

BY LEVI D. MOXNESS

CRITICAL MINERALS: MADE IN THE USA?

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

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

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

Promising Elements In Coal And Their Uses

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

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

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

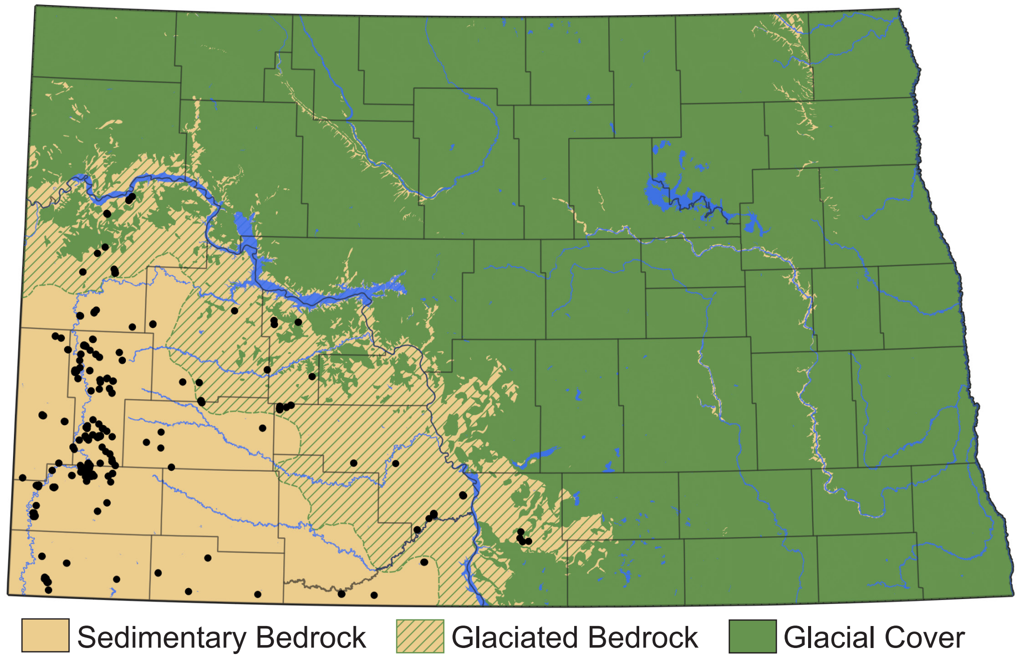

FIGURE 1.
NDGS samples (black dots) relative to the generalized erosional landscapes of North Dakota. Most of the state's bedrock surfaces were eroded and covered by glaciers as recently as the late Pleistocene. Other areas just southwest of the Missouri River were glaciated earlier in the Pleistocene,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

WHY COAL?

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

NDGS INVESTIGATIONS

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

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

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

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

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

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

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

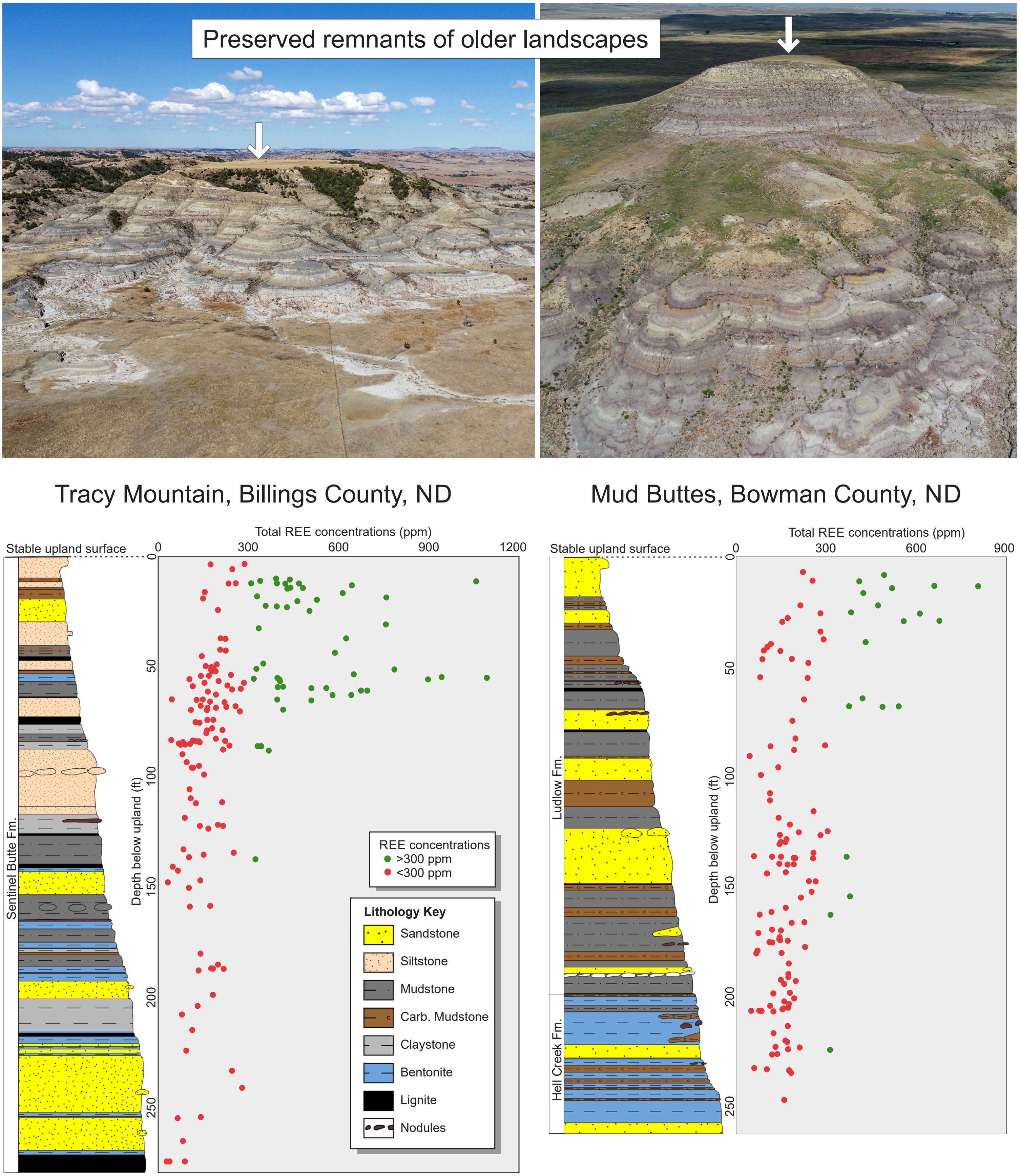

FIGURE 3.

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

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

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

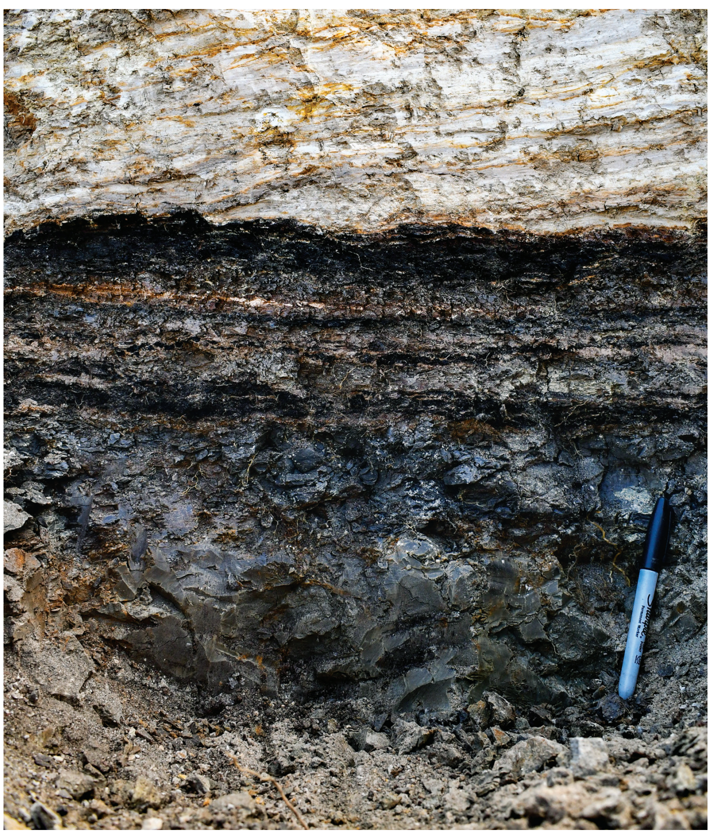

FIGURE 4.
A thin lignite (sample 2B from Moxness and others, 2021) beneath silty mudstone, roughly 20 feet below the top of Tracy Mountain, containing 1,054 ppm of rare earths. Marker for scale.

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A SIGNIFICANT FOSSIL COLLECTION COMES HOME

BY CLINT A. BOYD

Ferocious dinosaurs and towering mammoths are among the first things that come to mind for most people when the topic of fossils is mentioned. These engaging creatures capture the imagination, conjuring images of ancient North Dakota landscapes far different from anything we see here today. While the ghosts of the animals that roamed those environments will forever haunt our collective consciousness thanks to countless documentaries and blockbuster movies, accurately reconstructing these lost worlds requires studying all the evidence preserved in the fossil record. In particular, the study of fossilized plants (paleobotany) plays a crucial, and often underappreciated, role in understanding how the climate in North Dakota has changed over hundreds of millions of years.

The Paleocene Epoch spans from 66 to 56 million years ago (Cohen et al., 2013), an important interval of time immediately after the abrupt and brutal extinction of the non-avian dinosaurs. Rocks deposited during this time period record the early evolution of mammals as they rose from the ashes of the dinosaur dominated world. Extensive areas of western North Dakota are covered by Paleocene rocks of the Fort Union Group, making our state one of the best places in the world to study this key transition in the history of life on Earth. Fossilized plants are commonly found in these rocks, typically as large sections of petrified wood or carbonized imprints of leaves. A few fossil plant sites stand above the rest in terms of both the quality and quantity of the fossils they preserve. Arguably, the best of those sites in North Dakota is the Almont Fossil Plant Site: a treasure trove of fossils that provides a uniquely detailed snapshot of a moment from North Dakota's past. We are excited to announce that in the fall of 2022 a large collection of fossils from the Almont Fossil Plant Site was permanently transferred to the North Dakota State Fossil Collection.

HISTORY OF THE ALMONT SITE

The Almont Site consists of a series of small outcrops of mostly yellow-brown, finely laminated claystone that extend over hundreds of yards in the local area (Crane et al., 1990). The productive fossil layer is approximately 20 inches thick, sits above a green to gray sandstone, and is covered in most places by up to 18 inches of soil. The claystone is silicified, making it more resistant to erosion than a typical claystone and causes it to exhibit conchoidal fracture when it breaks. As a result of the fine laminations and the silicification, rocks from the site can be split along bedding planes, exposing the fossils preserved within (fig. 1). The fossils from the site are exquisitely preserved, in some cases even preserving minute cellular structures (Crane et al., 1990).

FIGURE 1.
Photograph of a large slab of plant fossils from the Almont Site showing the density of fossils typically recovered from the site. Colored arrows indicate different plant specimens on the slab. Each square on the scale bar at the bottom equals 10 mm.

Work at the Almont Site by museum crews began in 1982 (Crane et al., 1990), though collecting by locals and amateur fossil collectors likely began earlier. John Hoganson, a retired NDGS paleontologist, first visited the site in the fall of 1983 and immediately recognized its significance. Over the years NDGS paleontologists collected hundreds of specimens from the site and accepted donations of exceptional specimens collected from the site by local North Dakotans. The first scientific article to include material from the site was published in 1982 (Manchester and Dilcher) and over the ensuing 40 years, dozens of papers have been published on specimens from the site (e.g., Crane et al., 1991; Pigg and DeVore, 2005; Benedict et al., 2008; Zetter et al., 2011; Ickert-Bond et al., 2015). The site is located on private property and permission must be obtained before visiting the site or collecting specimens.

THE FLORA OF THE ALMONT SITE

The flora preserved at the Almont site is exceptionally diverse, with at least 50 species representing 30 different families of plants reported thus far (Ickert-Bond et al., 2015). By comparison, over 95% of documented Paleocene fossil plant localities preserve less than 10 species (Crane et al., 1990). By far, the most abundant fossils recovered at the site are leaves of a close relative of the modern *Ginkgo* tree: *Ginkgo cranei* (fig. 2). Other plants present at the site include members of the walnut family (Juglandaceae), the eucalyptus family (Myrtaceae), the dogwood family (Cornaeae), and the white pear family (Icacinaceae).

FIGURE 2.
A fossil *Ginkgo* leaf from the Almont Site in central North Dakota.

Leaves are the most common types of plant fossils found at the site, but a variety of other plant structures are also present (fig. 3). Fruiting bodies and other types of seed-bearing structures are known for multiple species at the site, including intricate fruiting bodies from a close relative of the modern bird's eye bush (figs. 3A-C). Flowers are also preserved for some species, including clusters of flowers from *Hamawilsonia boglei*, a member of the witch hazel family (Benedict et al., 2008).

Overall, the plants preserved at the site indicate a warmer and wetter environment than found in North Dakota today, more similar to temperate forests seen today in North and South Carolina (Crane et al., 1990). The types of plants preserved at the site, along with the abundance of fish fossils, indicate these fossils were deposited in an aquatic environment. The delicate preservation of the fossils and the finely laminated rocks present at the site rule out higher energy aquatic environments like rivers or streams, indicating the site likely represents a calm pond or lake environment.

VERTEBRATE FOSSILS FROM THE ALMONT SITE

While the Almont Site is best known for the beautifully preserved plant fossils, there are some fossils known from the animals that were living in this ancient lake. The best known of these is the extinct fish *Joffrichthys triangulpterus*, a distant relative of modern arowanas that grew to around 12 inches in length and is only known from the Almont Site (Newbrey and Bozek, 2000). This species is most commonly represented by isolated scales found mixed amongst the plant fossils, but a few nearly complete, well-preserved specimens are known (fig. 4). While the more complete specimens help paleontologists determine what the fish looked like and what it is related to, the large number of isolated scales preserved at the site also provide important information about this species that would otherwise be difficult to determine. As these fish grew during their lifetime each scale added a new layer of growth around the outer edge of the scale. As a result, paleontologists can count these growth rings to determine the age of the fish when it died, similar to counting tree rings to determine the age of a tree. By studying hundreds of these scales, paleontologists were able to understand how long these fish lived and even where they lived in the lake at different ages in their lives. The oldest fish was nine years old when it died, and the most common age encountered was three years old. Relatively few scales from fish that were less than three years old were identified at the site, suggesting that the younger fish preferred to live in a different area of the lake (Newbrey and Bozek, 2003). This separation of different ages of fish in different parts of a lake is known to occur in many species living today.

Another interesting aspect of the fish fossils from the site is that several were found in bird coprolites (fossilized feces). These fish bones were the only bones present in those coprolites. This indicates that there was a species of fish-eating bird living around this lake that was preferentially feeding on this fish species. It is exciting to think that we know about the presence of a species of bird at this site and even have insight into its preferred diet despite the fact that no bones from that bird species have yet been found at the site!

RECEIVING THE COLLECTION

In the spring of 2019, the North Dakota Geological Survey was contacted by Ray Reser at the University of Wisconsin-Stevens Point Museum of Natural History (UWSP) about their extensive collection of fossils from the Almont Site.

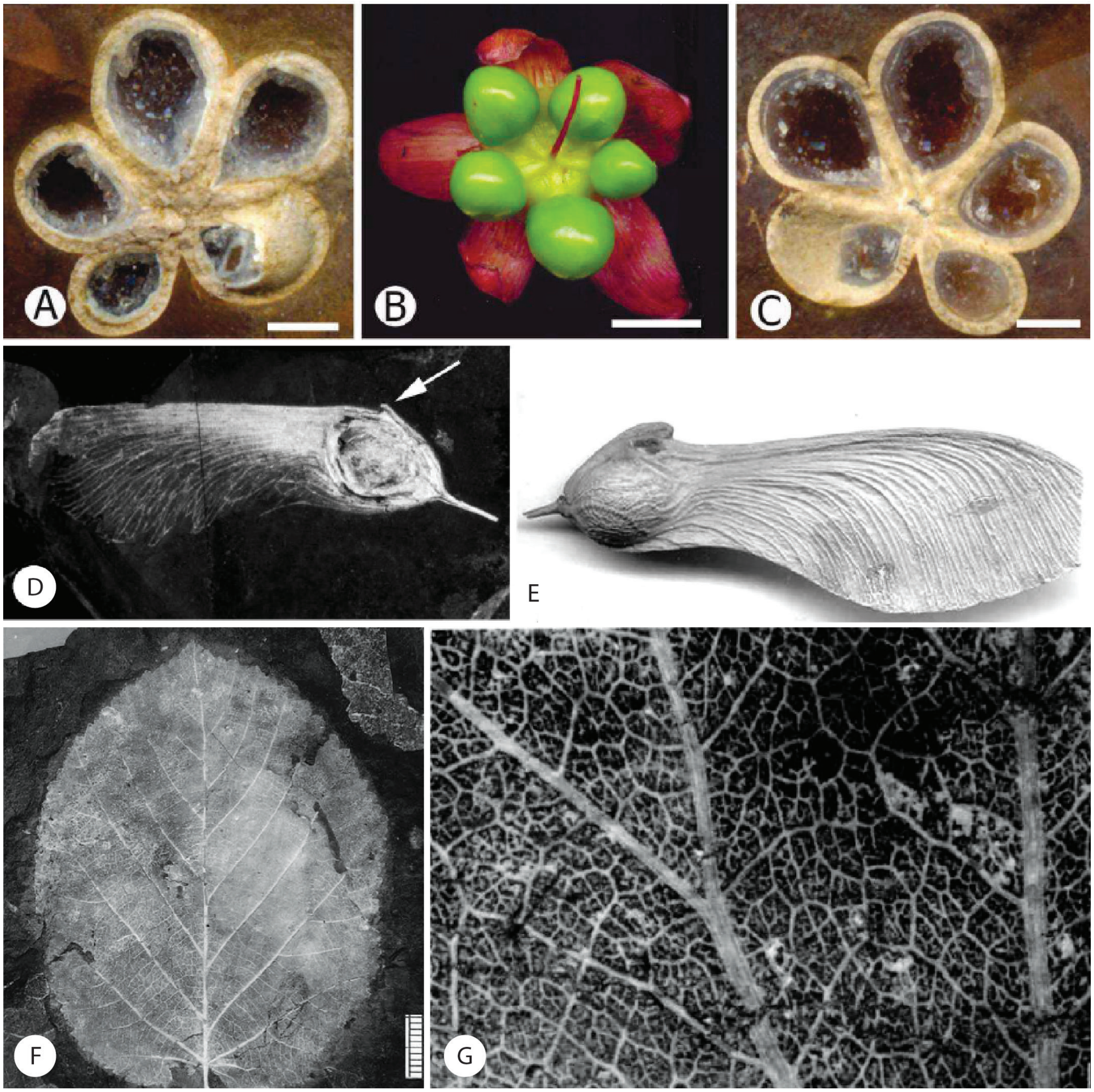

FIGURE 3. Examples of well-preserved plant fossils from the Almont Site. Fossilized fruiting bodies of the extinct plant *Paleoochna tiffneyi* (A and C) compared to a fruiting body from a closely related living species (B) (modified from Ickert-Bond et al., 2015: fig. 1A-C). Fossilized seed of the extinct plant *Paleosecuridaca curtisii* (D) compared to a seed from a closely related living species (E) (modified from Pigg et al., 2008: fig. 2a-b). A fossilized leaf from the extinct plant *Palaeocarpinus dakotensis* (F: modified from Manchester et al., 2005: fig. 7A). Close up view of the venation pattern on a fossilized leaf of the extinct plant *Zizyphoides flabella* showing the preservation quality of fossils from the Almont Site (G: modified from Crane et al., 1991: fig. 57). Scale bars 2 mm in A and C and 10 mm in B.

The UWSP spent years collecting thousands of specimens from the site, many of which have been used in scientific publications describing the overall flora preserved at the site and even for naming new plant species. The UWSP was downsizing its museum collections and they were attempting to identify other museums that were willing to take in parts of the collection. The North Dakota State Fossil Collection was a natural choice for the Almont Site specimens given that they were originally from here in North Dakota. We readily agreed to give these important specimens a home, and over the next few years the UWSP worked to get all of the material packed up and ready for the move.

In September of 2022, a small moving truck arrived from Wisconsin to deliver the collection. In all, 67 boxes of specimens, along with a dozen or so larger slabs that did not fit in boxes, were delivered into our care. In total, the collection numbers around 4,000 specimens, vastly outnumbering the number of specimens previously in our collection from the site. Volunteers are working with NDGS paleontologist Jeff Person to inventory and organize these fossils (fig. 5). As that work is completed for each box,

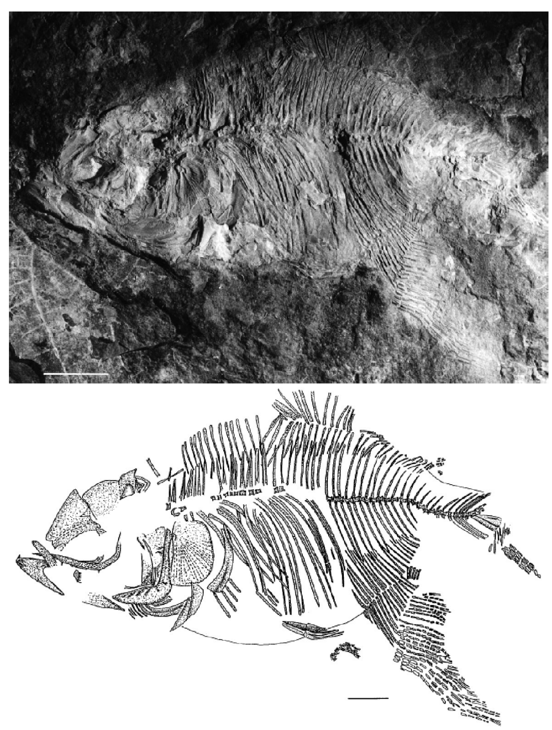

FIGURE 4. Image (top) and illustration (bottom) of the holotype of *Joffrichthys triangulpterus* (NDGS 13035), a fish only known from the Almont Site. Figure modified from Newbrey and Bozek (2000: figs 1 and 2). Scales bars equal 10 mm (top image) and 5 mm (bottom illustration).

the specimens are then moved into their permanent home in our collections facility (fig. 6). In total, we estimate the full Almont Site collection will fill three of our collections cabinets, or roughly 240 drawers, not counting the larger slabs that will have to be stored on our oversize shelving (fig. 1). Once this work is complete the collection will be available to researchers from across the world to examine, helping to improve our knowledge of North Dakota's prehistoric past.

FIGURE 5.
Volunteer Toni Neslen inventorying and organizing the newly delivered plant specimens from the Almont Site before their final placement in the collections cabinets.

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FIGURE 6.
One of the three collections cabinets filled with the newly delivered plant fossils from the Almont Site.

2023 PUBLIC FOSSIL DIGS

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

Opens Saturday, February 4 at 10am Central @ www.ndpaleofriends.org

MEDORA

This dig is co-sponsored by the North Dakota Geological Survey (NDGS) and the Theodore Roosevelt Medora Foundation.

After the non-avian dinosaurs went extinct, crocodiles became the dominant predator in North Dakota, and the environment was warm, humid, and swampy.

We will be digging in Sentinel Butte Formation rocks, 55-60 million years old.

This site is rich in a variety of swamp denizens, including crocodiles, giant salamanders, fish, champsosaurs, clams, snails, and more.

The rugged badlands in the nearby Theodore Roosevelt National Park may also be a draw for those not interested in digging in the dirt.

WHEN:

FULL DAYS:
June 15, 20, 21

FAMILY HALF-DAYS:
June 16, 17, 18 (AM & PM Sessions)

NEW! EXPERIENCED DIGGER 2-DAY SITE CLOSING:
June 22-23

WHERE:

Daily trips to the fossil site will originate from Medora, ND.

COST:

Full Day: $40 / Day
Family Half-Day: $30 / Day
Experienced Digger 2-Day: $70

DICKINSON

After a many-year hiatus, we will be returning to the scenic Little Badlands of North Dakota.

This Oligocene locality is ~32-30 million years old.

Of all the sites across North Dakota, this particular one holds the most mammals, and boasts the beginnings of many mammal groups still seen today. Hornless rhinos, three-toes horses, camels, entelodonts, nimravids, rodents, bats, eagles, toads, tortoises, alligators, and more.

PLEASE NOTE: This is a PROSPECTING site, not a quarry site - participants will need to be in good enough physical condition to hike in moderate to rugged terrain, and carry all of their supplies with them for the day. This site is not suitable for young children - only Full Days (15+ years) will be available. There are NO porta-potties and NO shade tents at this area.

WHEN:

FULL DAYS:
June 26-30

WHERE:

Daily trips to the fossil site will originate from the Dickinson Museum Center each morning.

COST:

Full Day: $40

BISMARCK

We will be working on a site that preserves a plethora of Hell Creek Formation (67 million-year-old) creatures, including lots of dinosaur bones.

Teeth from *Tyrannosaurus*, bones from *Triceratops* and *Edmontosaurus*, plus crocodiles and other creatures abound.

This experience will include working at an established quarry site, within easy walking distance of our vehicles.

Please read the Bismarck Area FAQ for more details.

WHEN:

FULL DAYS:
July 10-13, 19-20, 25-27, 31,
August 1-2

FAMILY HALF-DAYS:
July 14, 21, 28 (AM Sessions Only)
July 17, 24 (AM & PM Sessions)

EXPERIENCED DIGGER 2-DAY SITE CLOSING:
August 3-4

WHERE:

Daily trips to the fossil sites will originate from Bismarck, where we will meet at the Heritage Center.

COST:

Full Day: $60 / Day
Family Half-Day: $40 / Day
Experienced Digger 2-Day: $120

PEMBINA

This dig is co-sponsored by the North Dakota Geological Survey (NDGS) and the North Dakota Parks and Recreation Department.

We will be returning once again to the beautifully scenic Pembina Gorge in our ongoing search for sea monsters.

This Pierre Formation location, 80 million years old, holds some of the oldest surface rocks in North Dakota.

This was a time when North Dakota was covered by the Western Interior Seaway, and was home to great swimming reptiles called mosasaurs; giant squid, sea turtles, aquatic birds, large (and small) fish, snails, clams, and more.

WHEN:

FULL DAYS:
August 14-18

FAMILY HALF-DAYS:
August 11-13 (AM & PM Sessions)

NEW! EXPERIENCED DIGGER 2-DAY SITE CLOSING:
August 19-20

WHERE:

Daily trips to the fossil site will originate from Walhalla, ND.

COST:

Full Day: $40 / Day
Family Half-Day: $30 / Day
Experienced Digger 2-Day: $70

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.
- At all four dig locations, participants must bring their own lunches.
- Shade tents and porta-potties will be available on site EXCEPT at the Dickinson dig location.
- The Experienced Digger 2-Day Site Closing Sessions may finish early on the 2nd day.
- Our digs have a minimum age of 15 years for a Full Day and 10 years for a Family Half-Day. No digs for children under 10 years.
- NO PERSONAL VEHICLES - All participants will be transported by van from the meeting site to the dig site.

Please go to *www.dmr.nd.gov/dmr/paleontology/fossil-digs* for more information and additional rules for participants.
More information on early registration opportunities is available at *www.ndpaleofriends.org*

PRELIMINARY CASE STUDY OF

MIDDLE THREE FORKS CO-DEVELOPMENT INFLUENCE UPON UPPER THREE FORKS WELL PERFORMANCE

Within The Bakken-Three Forks Petroleum System

BY TIMOTHY O. NESHEIM

INTRODUCTION

Exploration and development of the Bakken Petroleum system as a modern unconventional oil play (horizontal drilling coupled with hydraulic fracture well completions) began in the mid-2000s within western North Dakota (Nordeng et al., 2010). While initial exploration and development focused on the Middle Bakken reservoir, the upper Three Forks evolved into a second primary reservoir during the late 2000s (fig. 1) (Gaswirth and Marra, 2015; Nesheim 2019). To date, more than 17,500 wells have been drilled and completed within the Middle Bakken and upper Three Forks Formations (USGS, 2021).

Horizontal drilling in the middle Three Forks began in late 2012 followed by initial well completions and production in early 2013 (Nesheim, 2020a). By the end of 2020, more than 250 horizontal middle Three Forks wells had been drilled and completed with combined cumulative production of more than 57 million barrels of oil and 120 billion cubic feet of gas (fig. 1 and 2) (Nesheim, 2020a). Middle Three Forks hydrocarbon charge appears concentrated within the central, deepest portions of the Williston Basin where the Lower Bakken shale is both relatively thick (≥20 feet) and at its highest levels of thermal maturity, generating enough hydrocarbon volume to migrate downwards to charge not only the upper Three Forks but the underlying middle Three Forks as well (Nesheim, 2019).

While hundreds of productive horizontal wells have been drilled and completed within the middle Three Forks, questions remain regarding the development of the unit. One important set of related questions: how does middle Three Forks horizontal well development influence

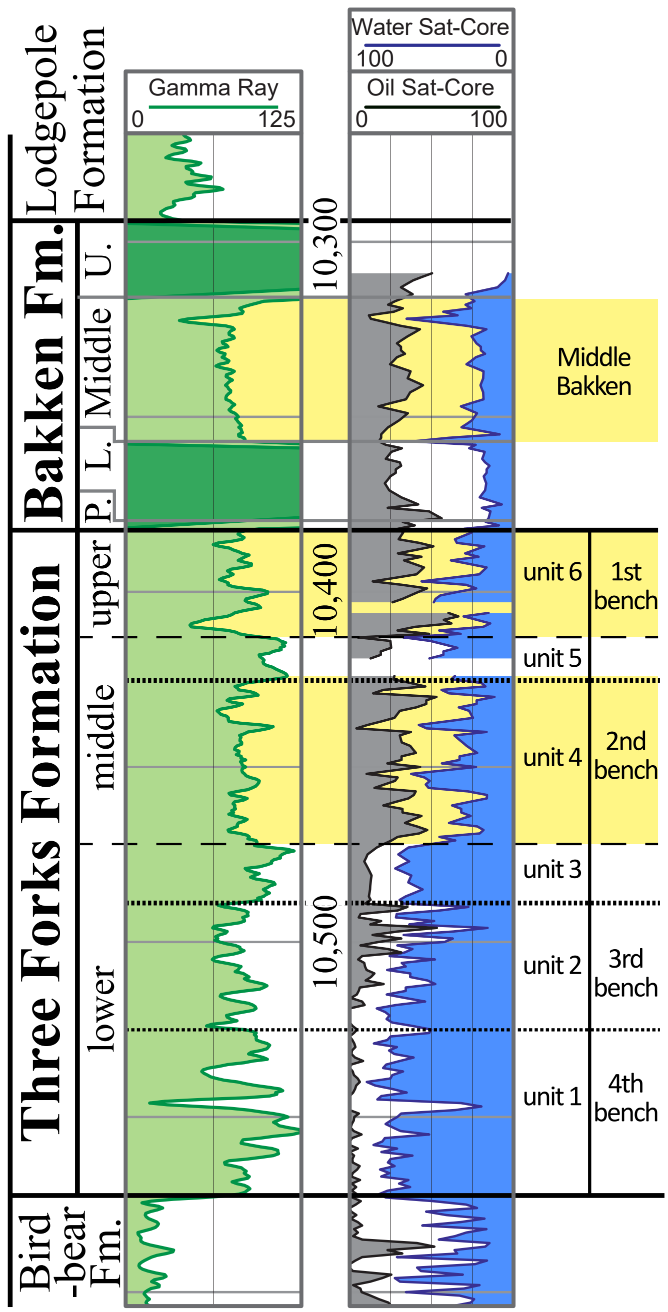


FIGURE 1.
Gamma-ray wireline log example of the Bakken-Three Forks section with core-plug oil and water saturation data from Enerplus Resource's Hognose 152-94-18B-19H-TF (NDIC: 26990; API: 33-053-05475-00-00). Upper-middle-lower Three Forks stratigraphic nomenclature system is from Bottjer et al. (2011), and the 6-unit subdivision system is from Christopher (1961; 1963).

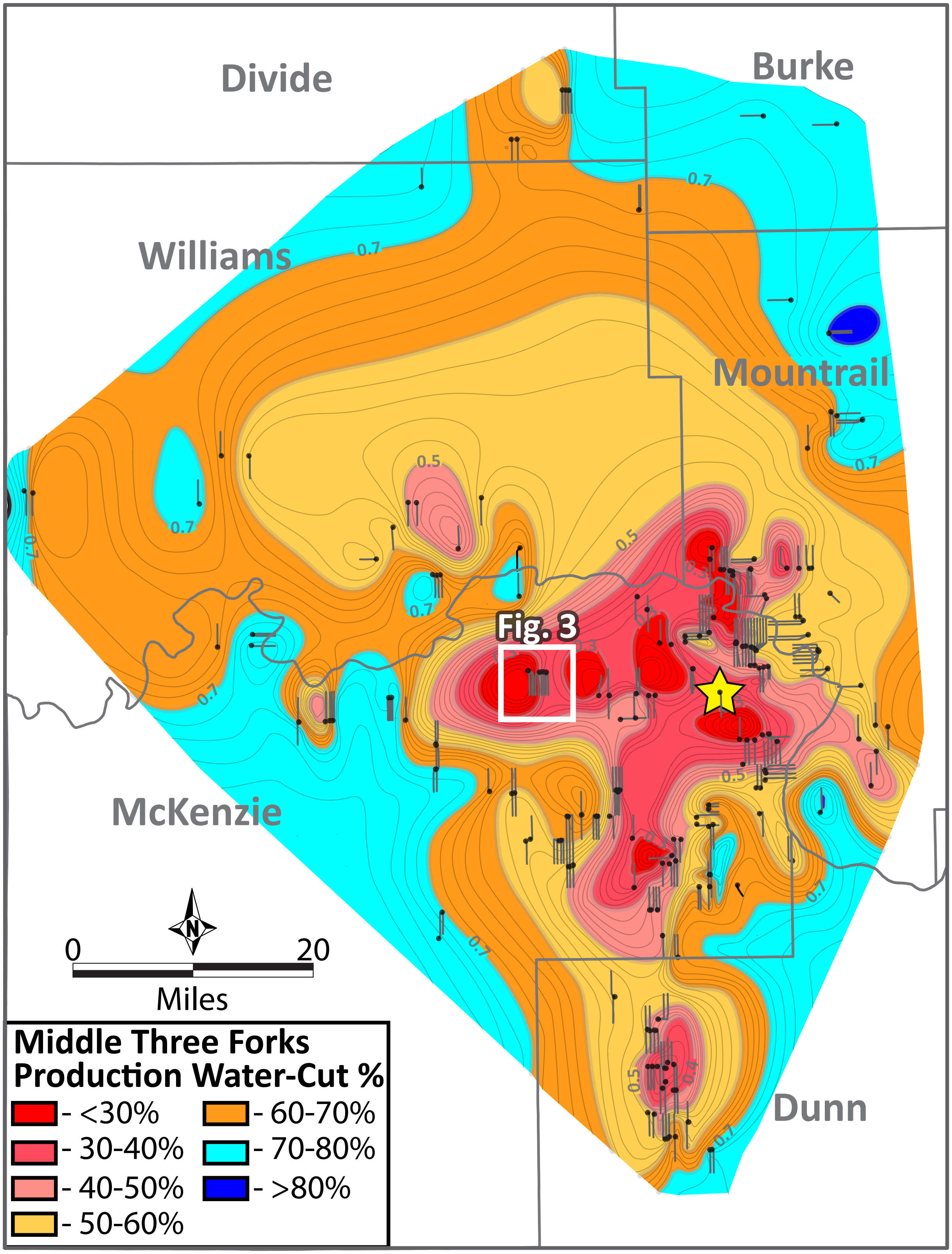


FIGURE 2. Contour map depicting calculated middle Three Forks water-cut from horizontal well production. Water-cut contours are in 0.01 fractional increments. Black dots and lines represent surface locations and corresponding horizontal boreholes for middle Three Forks wells. The white outline depicts the Figure 3 map area and the yellow star depicts the location of the Figure 1 well location. Modified from Nesheim (2020b).

production from horizontal wells drilled and completed within the overlying upper Three Forks? How much oil and gas production from middle Three Forks horizontal wells comes from the overlying upper Three Forks reservoir? When the middle Three Forks is co-developed within the upper Three Forks, are the co-developed upper Three Forks wells less productive than when the middle Three Forks is not co-developed?

In order to evaluate the effect of middle Three Forks co-development on upper Three Forks production, a preliminary case study was completed comparing upper Three Forks production in adjacent areas both with and without middle Three Forks co-development. The Twin Valley Field area (figs. 2 and 3) was selected for this case study for several reasons: 1) location within the area of middle Three Forks hydrocarbon charge (Nesheim, 2019),

2) co-development of the Middle Bakken, upper Three Forks, and middle Three Forks reservoirs with approximately 3-4 wells per target horizon per 1280-acre spacing unit, and 3) field area is removed from any major documented structure (e.g. Nesson anticline). If middle Three Forks co-development has a negative effect on upper Three Forks production, then upper Three Forks wells should be more productive in spacing units without middle Three Forks development.

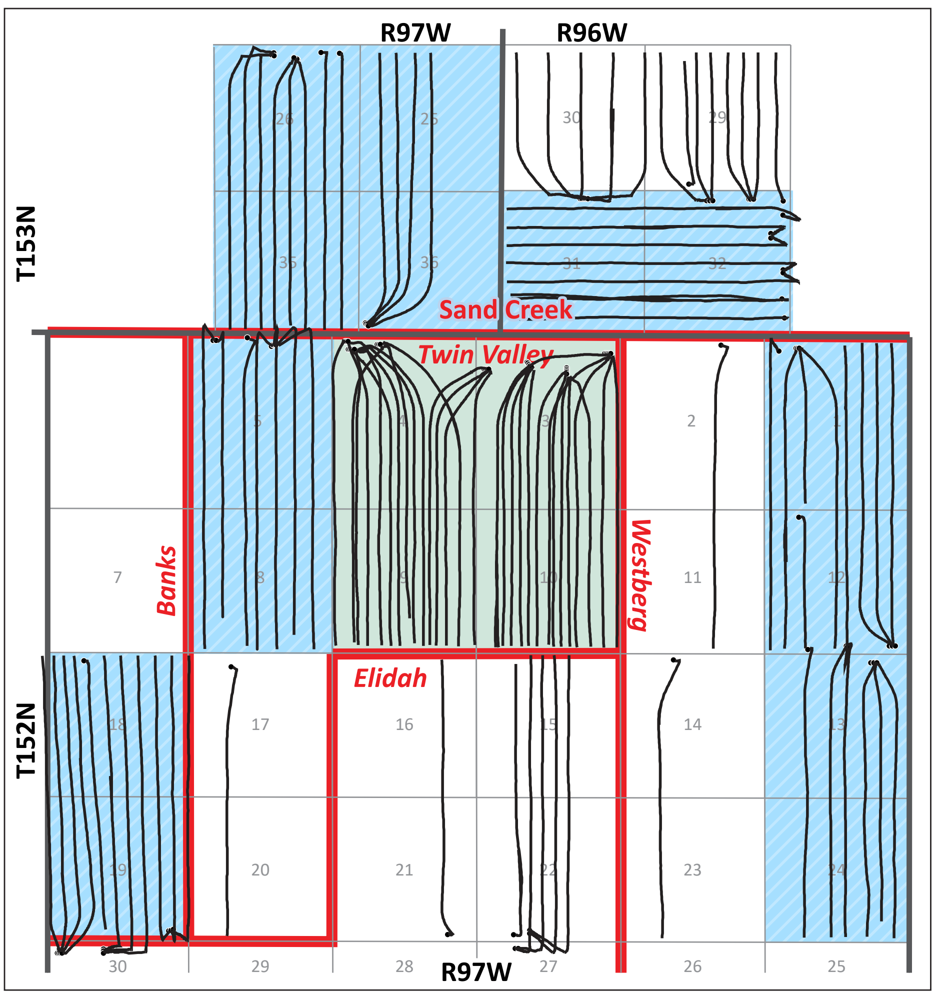
METHODS

Well log information and drilling records were reviewed to determine the primary landing zone of each horizontal well within the study area (Fig. 3). Production records of all horizontal upper Three Forks wells were compiled and plotted with cumulative oil production versus number of productive months to evaluate upper Three Forks well production between the area of middle Three Forks co-development versus areas without middle Three Forks co-development (fig 4).

RESULTS

A total of 10 upper Three Forks horizontal wells were identified within the Twin Valley field with the following criteria: ~2-mile laterals, 12+ months of production, and located in spacing units containing co-development of the underlying middle Three Forks (fig. 3 and 4). An additional 17 upper Three Forks horizontal wells with ~2-mile laterals and 12+ months of production were identified within adjacent/nearby spacing units that have not had middle Three Forks co-development to date. All of these upper Three Forks wells were completed during 2013-2019, when multi-stage hydraulic fracturing was a common practice by operators in the Bakken-Three Forks play.

Cumulative production totals of the upper Three Forks wells range from approximately 160k - >700k barrels of oil (fig. 4). Overall, production from the upper Three Forks wells in spacing units with middle Three Forks co-development is generally equal to or exceeding production from upper Three Forks wells in spacing units without any middle Three Forks development (fig. 4). At the 3-year (36 months) and 5-year (60 months) marks, upper Three Forks wells with co-middle Three Forks well developed average 416k and 465k barrels of cumulative oil production per well while the adjacent upper Three Forks wells without middle Three Forks development averaged 202k and 251k barrels (fig. 4). So not only are the upper Three Forks wells with middle Three Forks co-development not any less productive, but instead have been more productive than the adjacent upper Three Forks wells. Furthermore, middle Three Forks horizontal wells within the Twin Valley field have outperformed many of the proximal, adjacent upper Three Forks wells without co-development. Middle Three Forks wells in the study area have averaged 341k and 399k barrels of cumulative oil production at the 3-year and 5-year marks (fig. 4). Based upon these preliminary results, middle Three Forks co-development does not appear to have negatively influenced upper Three Forks well performance within the Twin Valley field area.



DISCUSSION

Additional factors beyond the co-development of the middle Three Forks likely contribute to some degree upon the variation in upper Three Forks well production across the study area. While the study area is relatively small, minor geological variations including reservoir

FIGURE 3.
Twin Valley field area with section, township, and range location information. Black lines depict horizontal wells drilled within the Bakken or Three Forks Formations. Red lines and labels are oil and gas field outlines and names. The field area is depicted on Figure 2. Green shaded areas depict 1280-acre spacing units with co-development of upper and middle Three Forks reservoir. Blue shaded areas with white diagonal lines depict 1280-acre spacing units with only upper Three Forks reservoir development (no middle Three Forks co-development).

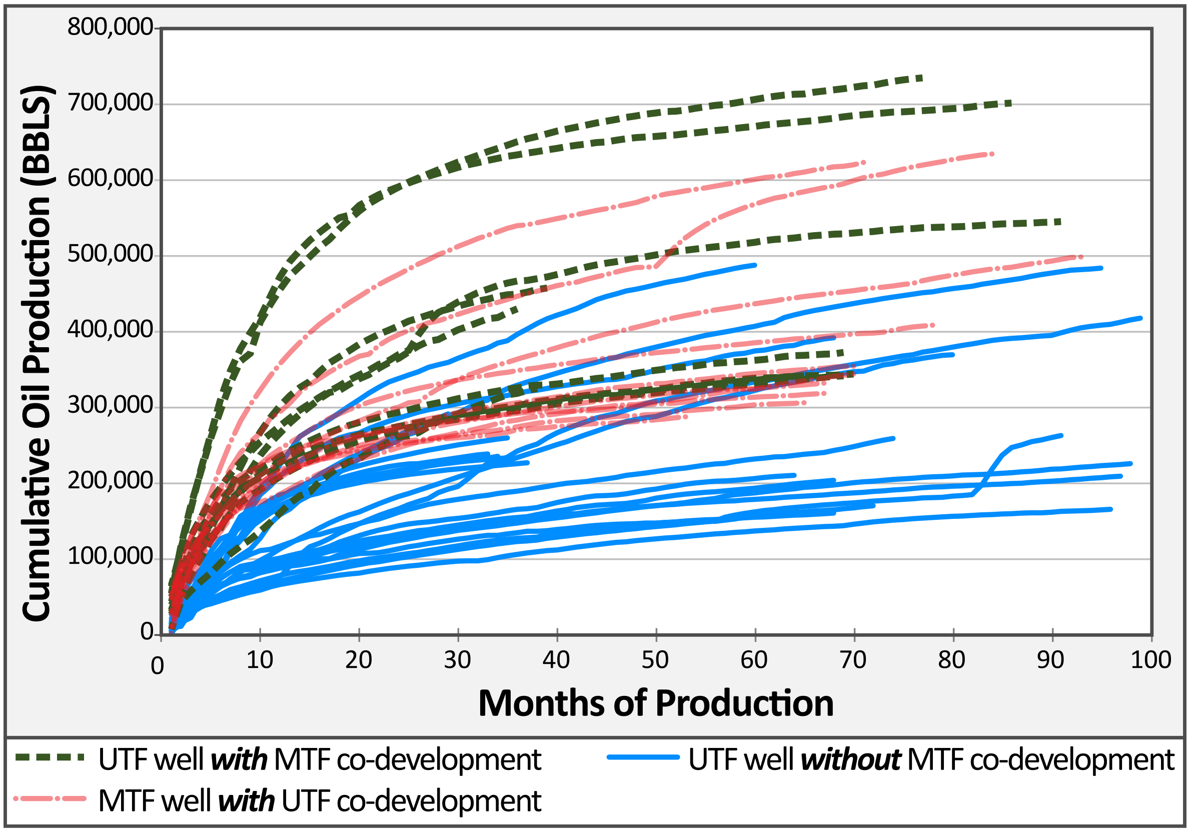


FIGURE 4. Cumulative oil production curves for upper and middle Three Forks horizontal wells from the Figure 3 field area with 12+ months of production data.

quality and structure (faulting and fracturing) may occur that influence production. Furthermore, variations in drilling (horizontal borehole positioning within the target interval) as well as completion style (e.g. number and type of hydraulic fracture stimulation stages) likely occur between the wells that influences short and long-term well performance. Examining these additional variables may lead to more insights into the best practices in drilling and completing wells in both the upper and middle Three Forks.

Looking at the current distribution of the 250+ productive middle Three Forks horizontal wells with relatively low water cut (<50%), 100s to 1,000s of potential infill development wells may be warranted within the unit (fig. 2). Still, a more expansive and detailed study of the middle Three Forks is needed, including a more detailed understanding of the middle Three Forks co-development influence/effect on upper Three Forks well performance.

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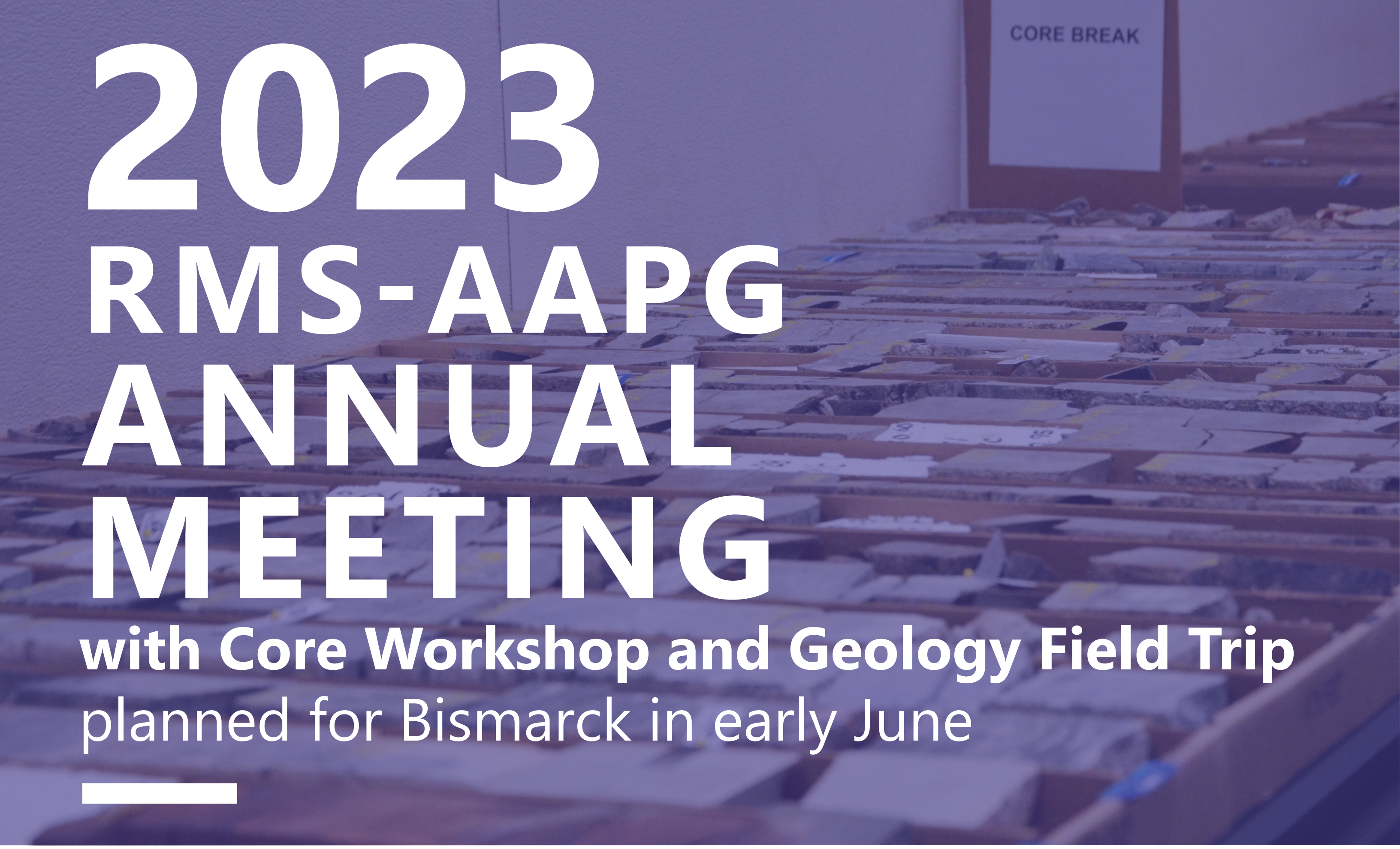


2023 RMS-AAPG ANNUAL MEETING

with Core Workshop and Geology Field Trip

planned for Bismarck in early June

In conjunction with the 2023 RMS-AAPG annual meeting, the North Dakota Geological Survey is organizing and running a pre-conference Williston Basin Core Workshop June 3 & 4 in Bismarck, North Dakota.

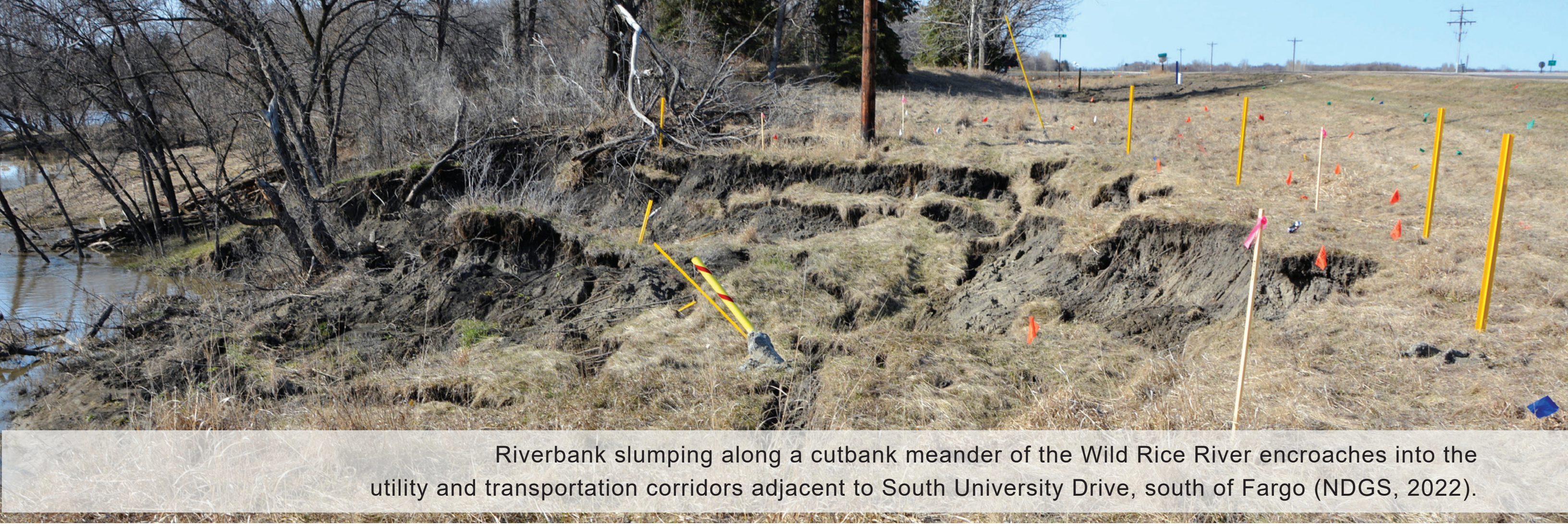
This 2-day core workshop will feature multiple core-based presentations spanning the Williston Basin sedimentary section including, but not limited to: Bakken and Three Forks Formations, Mississippian Madison Group, Cambrian-Ordovician Deadwood Formation, and Permian Broom Creek Formation.

In addition, the June 4-7 RMS-AAPG annual meeting will include technical geology material from across the Rocky Mountain region (including the Williston Basin) with information on petroleum geology, carbon sequestration, lithium and rare earth element (REE) resources.

Also, a post-conference 2-day field trip is planned, which will examine the Late Cretaceous and Paleogene history of southwestern North Dakota, with secondary focuses on associated geohazards, critical minerals, and geomorphology of the North Dakota badlands.

For additional information and core workshop, RMS-AAPG annual conference, and field trip registration, visit the following website:

www.rms-aapg2023-bismarck.com


Riverbank slumping along a cutbank meander of the Wild Rice River encroaches into the utility and transportation corridors adjacent to South University Drive, south of Fargo (NDGS, 2022).

GEOLOGISTS SEE CONTINUED GROWTH

in Civil and Energy Construction Activity in North Dakota

BY FRED J. ANDERSON

As a part of their daily duties, North Dakota Geological Survey geologists review the geological suitability of environmental and engineering projects across the state. Since 2015, over 1,000 projects have been reviewed to mitigate potential geologic hazards at these project locations (fig. 1). Survey geologists work closely with scientists, engineers, and planning staff in the private and public sectors such as the Department of Water Resources, Environmental Quality, Transportation, Emergency Services, and Public Service Commission. Project reviews come to our office by way of the requirements of the National Environmental Policy Act of 1969, which requires a collective review of planned civil infrastructure projects in order that all social, economic, and environmental effects are considered.

These project reviews are commonly initiated by environmental and engineering consulting firms seeking comments from various agencies on issues that may have an impact on proposed projects. Requests to review infrastructure projects also come from state and federal agencies. This is where Survey geologists act in an advisory capacity to other agencies on siting and suitability especially when new waste disposal sites are located or proposed for expansion. The Department of Environmental Quality has worked closely with Survey geologists during the pre-application phase to identify any geologic conditions that may be unsuitable for the location of a new or expanding solid waste facility.

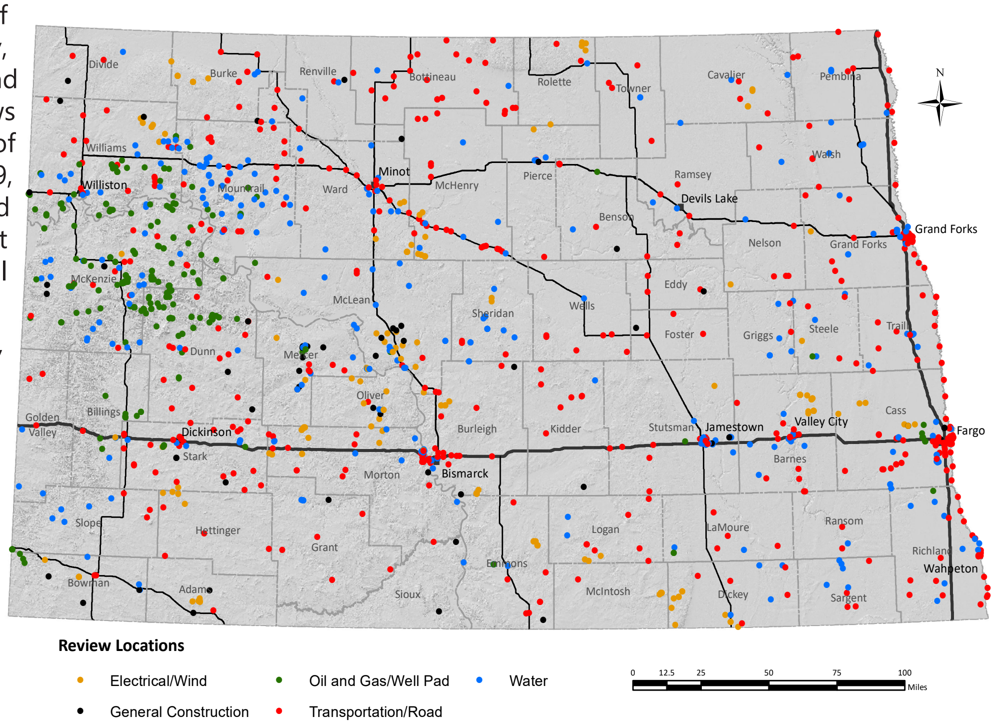


FIGURE 1. Location and types of projects reviewed for geologic suitability 2016-2022.

Back in the '70s and '80s, before a formal review process was created, it was common for solid waste disposal to find its way into old sand and gravel pits. Survey geologists engaged other regulators to end this practice.

Over the last 20 years, the number of reviews completed annually by Survey geologists has increased over five-fold from around 50 in the mid-2000s to well over 250 in 2022 (fig. 2).

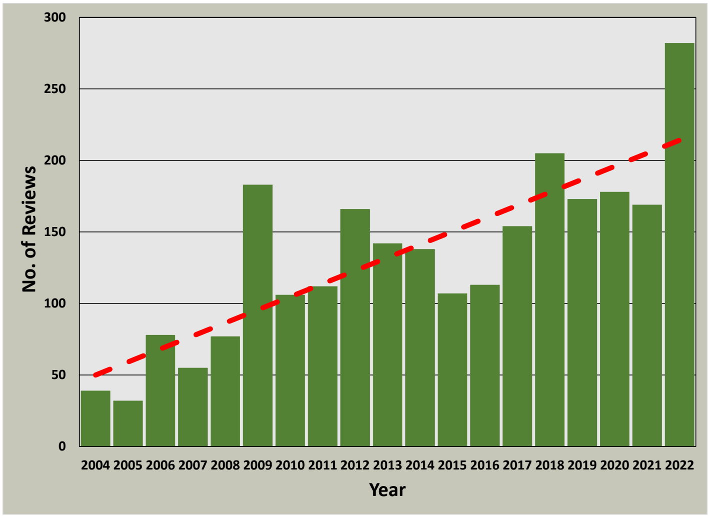


FIGURE 2.
The number of geologic reviews completed by Survey geologists continues to climb (green columns). Lately, these projects are transportation-related, consisting of bridge and structure replacements and roadway improvements.

TYPES OF PROJECTS

The types of projects that Survey geologists commonly review fall broadly into the energy and civil infrastructure sectors and consist dominantly of wind farms, oil and gas pipelines, roadway improvement projects (consisting dominantly of bridge replacements), and water and sewer line upgrades in urban and rural environments. General construction projects such as new facility or building expansions are also occasionally reviewed. Geologic reviews of coal mine permits and solid waste facility siting are also included in this geologic review program.

WIND

Wind projects continue to increase across the state as well (fig. 3). To date there are 2,157 wind turbines in service across the state (NDPSC, 2022) and there are nine new wind farms being proposed for construction in the coming years. Some locations are starting to approach their end of life where older outdated turbines are being decommissioned, such as two wind turbines south of Minot.

The two wind towers, south of Minot and one mile southeast of the old U.S. Air Force radar base along Highway 83, were some of the first wind towers constructed in North Dakota. These towers were operated by Basin Electric as part of the Minot Wind Facility. Known as "Willy and Wally," these two towers were removed this past spring (fig. 4), after 20 years of service. The towers were located on the southern end of the Max Moraine which marks one of the later glacial ice advances into North Dakota (Bluemle, 1989). These towers were positioned at topographically higher elevations than the surrounding area which enabled them to harness the winds rising across the Missouri Coteau.

In other parts of the state, such as south-central North Dakota near Wishek, a new $390 million dollar wind energy facility with as many as 74 new wind towers is being proposed (fig. 5) along the western margin of the Missouri Coteau at the edge of the Burnstadt end moraine. The northeastern part of the project will be located on hummocky end moraine sediments up to 300 feet thick. The southwestern part of the project will be located on the gently rolling topography created from subglacial clayey till sediments (Napoleon Drift) deposited around 38,000 years ago (Clayton, 1962).

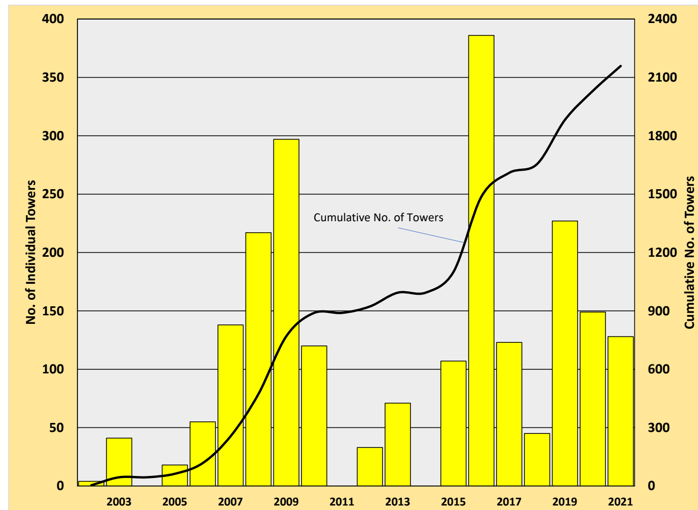


FIGURE 3.
The number of wind towers in operation in North Dakota continues to increase with new projects being proposed on nearly an annual basis (NDPSC, 2022).

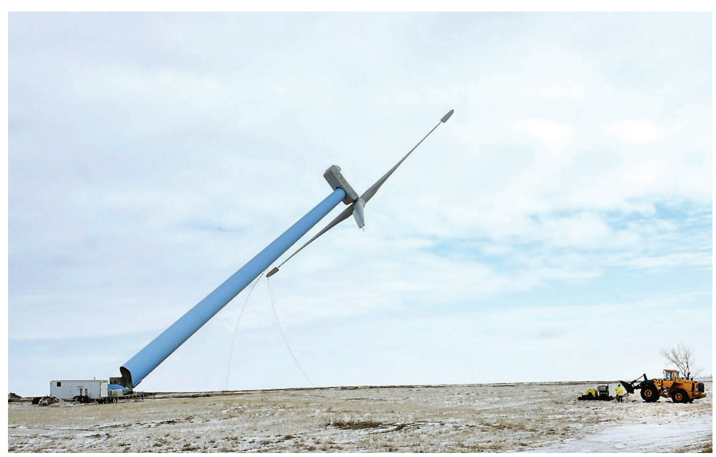


FIGURE 4.
Decommissioning of the first wind towers in North Dakota south of Minot. This process is called chop and drop, similar to felling a large tree, where the base of the tower is cut and the tower is pulled over with cables and heavy equipment (Image by Jill Schramm, Minot Daily News).

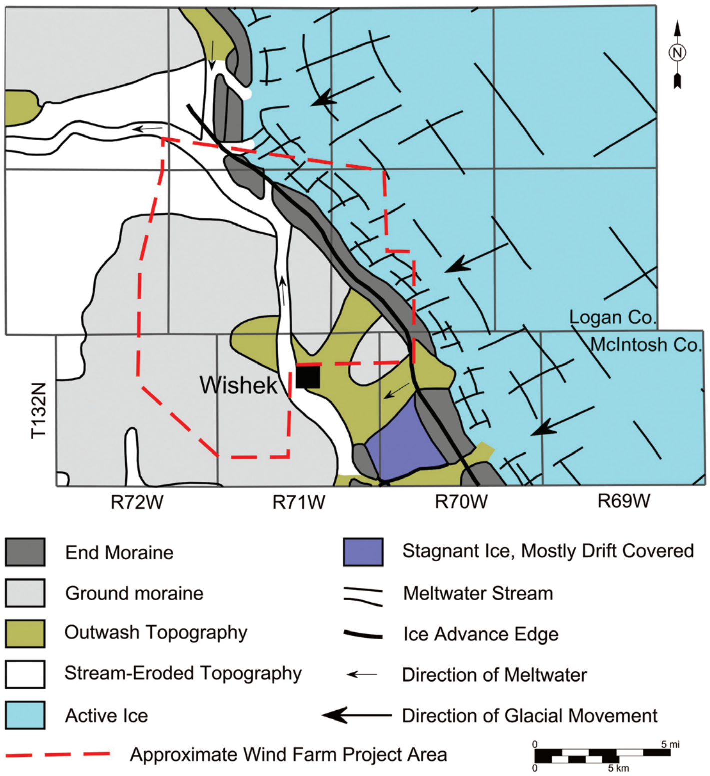


FIGURE 5.
The location of the proposed Badger Wind Energy Facility project area west and north of Wishek, North Dakota. This 251.6 MW facility, with as many as 74 proposed wind towers, is projected to be located on the western margin of the Missouri Coteau. This marks the edge of the Burnstadt end moraine, marking the edge of the last glacial ice advance in this area around 10,000 years ago (modified from Clayton, 1962).

FIGURE 6.
Aerial view of wind-tower foundation construction in the Souris River Valley in 2005 from an aerial photographic survey completed by the author. Towers are commonly bolted to reinforced concrete spread footings up to 70 feet wide and as much as 15 feet thick, depending on the geotechnical conditions encountered at each location. This provides for a stable base weighing in at around 1,400 tons (which is roughly the mass equivalent of eight Blue Whales).

These areas consist of gently rolling hills which are not associated with landslide development. The glacial sediments deposited in these areas consist of stony, sandy, silty types of clay-rich sediments that are generally well suited for construction activities.

In addition to the geologic review of the suitability of the entire wind farm project area, each turbine location is reviewed for its potential to be located near geologic hazards such as landslides or unstable soils (fig. 6). This is done both when the project siting application is first proposed and at the time of the filing of the Ten-Year Plan. When companies file their ten-year plans with the NDPSC, as required by law, notice is provided to the Survey. The Survey then takes the opportunity to review the location of the proposed or existing project and wind-tower locations against updated aerial imagery to determine if any recent changes to the landscape have occurred that could have an adverse effect on the structures. Landslide area maps, recently updated with high-resolution elevation data collected from LiDAR surveys, are available across the entire state. North Dakota is one of the first states in the nation to have completed a baseline landslide inventory for the entire state. This inventory now serves as a benchmark for future landslide and slope stability investigations.

TRANSPORTATION

Many of the state's aging bridges and structures on roads are being proposed for upgrades or full replacement by the NDDOT. Over the past eight years, the locations of just over 200 bridges or structures, such as culverts, have been reviewed during the replacement process (fig. 2). Most of these structures occur where county roads cross local rivers and streams. Knowing where potential landslides or unstable slopes may be at these crossings is important when considering structure replacement or repair of slopes affected by riverbank slumping (fig. 7).

WATER

Many municipalities across the state have been updating and improving their water and sewer lines and expanding water supplies to rural users. For example, the City of Galesburg is located on 50 to 120 feet of sandy silt of the Galesburg Delta in southwestern Traill County (fig. 8). The city is preparing to replace their aging water and sewer line system with nearly four miles of new line planned (fig. 9).

OIL AND GAS PRODUCTION INFRASTRUCTURE

Oil and gas pipelines and natural gas processing plants continue to expand across western North Dakota to meet

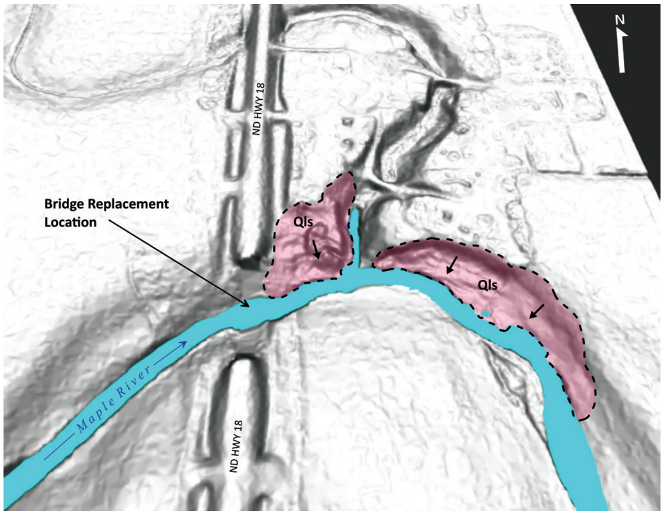


FIGURE 7.
This proposed structure replacement on ND HWY 18 crosses a reach of the Maple River where considerable slumping along the northern riverbank has been occurring as can be seen in this 3D surface model of the bridge location created from LiDAR elevation data. This bare earth LiDAR surface model artificially removes structures from the data (in this case the existing bridge). Areas of slumping (Qls) are occurring along the riverbank in close proximity to the bridge and are being closely monitored by the NDDOT.

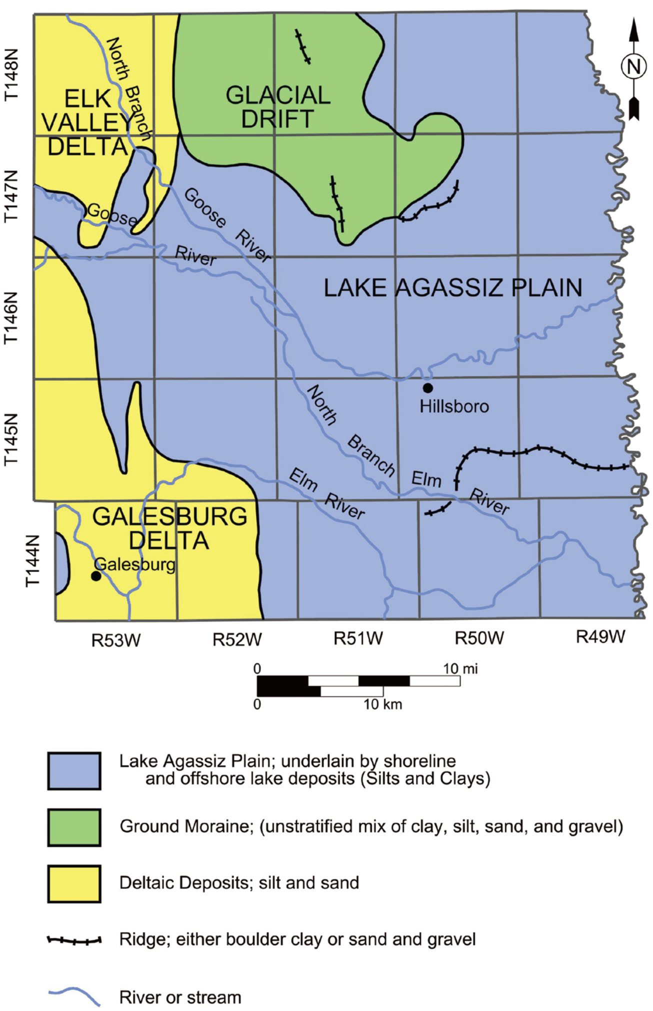


FIGURE 8.
The generalized geology of Traill County, North Dakota (modified from Bluemle, 1967).

FIGURE 9.
The City of Galesburg, in eastern North Dakota, will be updating their water and sewer infrastructure in 2023, replacing old worn-out clay piping with newer PVC or HDPE lines like these from a recent sewer upgrade project in Larimore (Image courtesy of AE2S, 2021).

increasing production demands. Since 2015, over 2,563 miles of pipeline corridor have been reviewed for geologic suitability, most importantly that these corridors are free of landslides and unstable areas. One of the more recent oil pipeline projects to be reviewed is the Bridger 16-inch crude oil line proposed to traverse across southern McKenzie and northwestern Golden Valley counties. By using our landslide mapping information in the route planning process, this 80-mile route bypasses the heavily landslide populated Little Missouri Valley. Choosing instead, a route where topographic and geologic conditions are more suited to pipeline placement (fig. 10). Areas that have potential to be problematic for pipeline placement are generally bypassed by route realignment during the design phase or by using directional drilling methods during construction, if rerouting is not possible.

ELECTRICAL GENERATION AND TRANSMISSION

The siting of electrical transmission lines, often associated with wind farm development, are also reviewed in our program. One of the more interesting electrical projects of late is the Harmony Solar project, proposed for construction in northeastern Cass County. When completed, this facility will be capable of adding 200 MW of electrical generating capacity, enough to supply the annual energy needs of

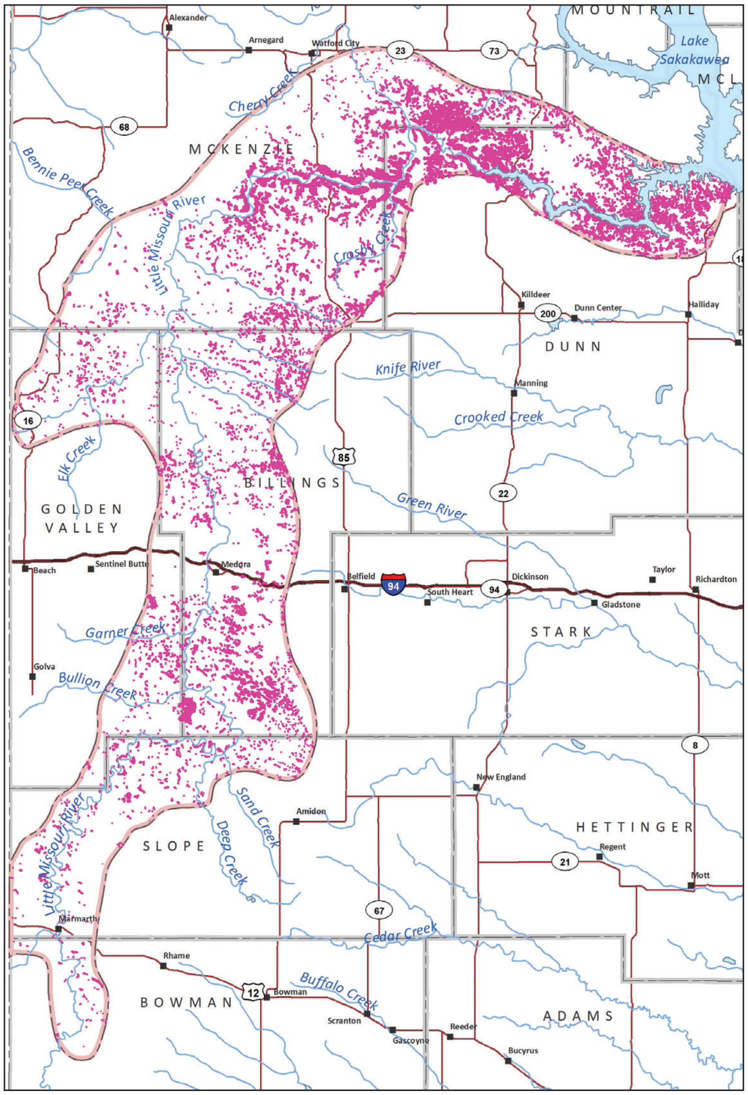


FIGURE 10.
The Little Missouri Badlands physiographic province (boundary as modified from Clayton, 1980) contains the highest density of landslide areas in North Dakota. As of this writing, over 10,490 landslides covering 97,600 acres (or 5.2% of this area) have been mapped. As updated maps are completed in this area, these numbers will continue to increase.

potentially tens of thousands of homes (Harmony, 2018). This solar energy facility is to be located just four miles northeast of Casselton in the southwestern portion of the Lake Agassiz plain (fig. 11). The soft and expansive offshore lacustrine clays of the Brenna Formation were noted in the shallow subsurface in this area during the review process. Since these clays are known to be problematic for construction projects throughout the Red River Valley, an extensive geotechnical evaluation of this area was completed as a part of the design and siting application process.

Survey geologists continue to review an increasing variety and number of civil and energy construction projects. These reviews serve to increase our state's mitigation effectiveness and efficiency, significantly reducing the potential costs associated with costly remedial measures that are required when projects are sited in geologically undesirable areas.

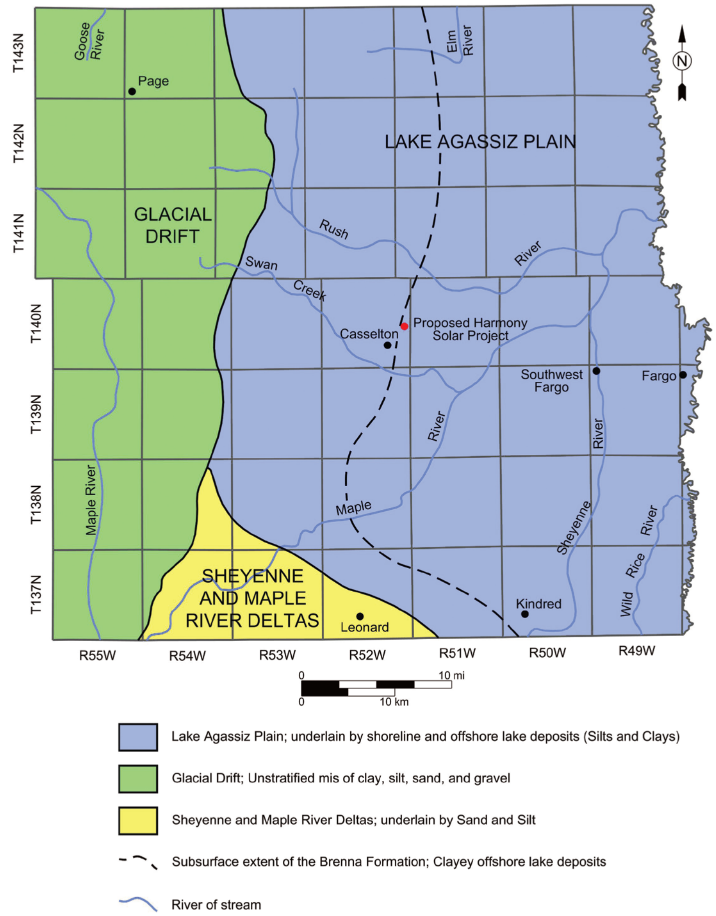


FIGURE 11.
Generalized surficial geology and extent of the offshore lake clays of the Brenna Formation in the southwestern Red River Valley (modified from Klausing, 1968).

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LANDSLIDES THROUGH TIME:

ACTIVE AND DORMANT LANDSLIDES IN EASTERN NORTH DAKOTA

BY BENJAMIN YORK AND CHRISTOPHER MAIKE

North Dakota is commonly associated with having a gently undulating landscape, so many people do not think of landslides having an impact on the state. However, nearly 50,000 landslides have been mapped statewide by the North Dakota Geological Survey (NDGS) since 2003. These landslides occur in many locations statewide (fig. 1) with most of them being in waterway systems (Red River, Sheyenne River, etc.), the Pembina Gorge (failing Pierre Shale), and the badlands in western North Dakota (Bullion Creek and Sentinel Butte Formations). Historically, the NDGS used an inventory style of mapping to map landslides, meaning all identifiable landslides were mapped. There was no distinguishing between an active or dormant type of slide.

At the NDGS, Phase I of landslide mapping began in 2003 and went through 2017 which included the publication of nearly 300 landslide maps (Maike and Moxness, 2022), using 1:20,000 aerial photographs from the 1950s and 1960s. These photos were looked at with a stereoscope, which gives a three-dimensional effect to the viewer. Over time, higher resolution satellite data became available along with Light-Detection and Ranging (LiDAR) and beginning in 2017, the NDGS used LiDAR and the satellite imagery in conjunction with stereopairs to continue mapping landslides across the state. The landslide maps using these products would now be known as Phase II. LiDAR is a remote sensing technology using lasers from an aircraft to create a digital elevation model of Earth's surface (Maike, 2016). LiDAR data was a game changer for interpreting landscapes for slides and failures. Through computer modeling, vegetation could be removed from the digital elevation models, allowing geologists to observe the "bare-earth." This vastly increased the number of landslides mapped by the NDGS (Moxness, 2019, 2022; Maike, 2021; Maike and Moxness, 2022). Currently, the Geological Survey is nearing completion of the Phase II landslide mapping program. The NDGS began Phase III landslide mapping on the eastern side of the state in 2021.

Phase III landslide mapping brings the 21st century into the mapping world. Phase III utilizes two North Dakota LiDAR datasets collected in the same area, typically 8-10 years apart (the current data availability). The second raster is subtracted from the first raster to calculate the elevation change. Negative values would signal erosion or net loss whereas positive values would signal accretion or net gain. Over a period of 8-10 years there may be many reasons for positive or negative displacement besides landslides. The interpretation for Phase III landslide mapping needs to be conducted by an individual with a great amount of experience with satellite imagery, LiDAR interpretation, and slope stability.

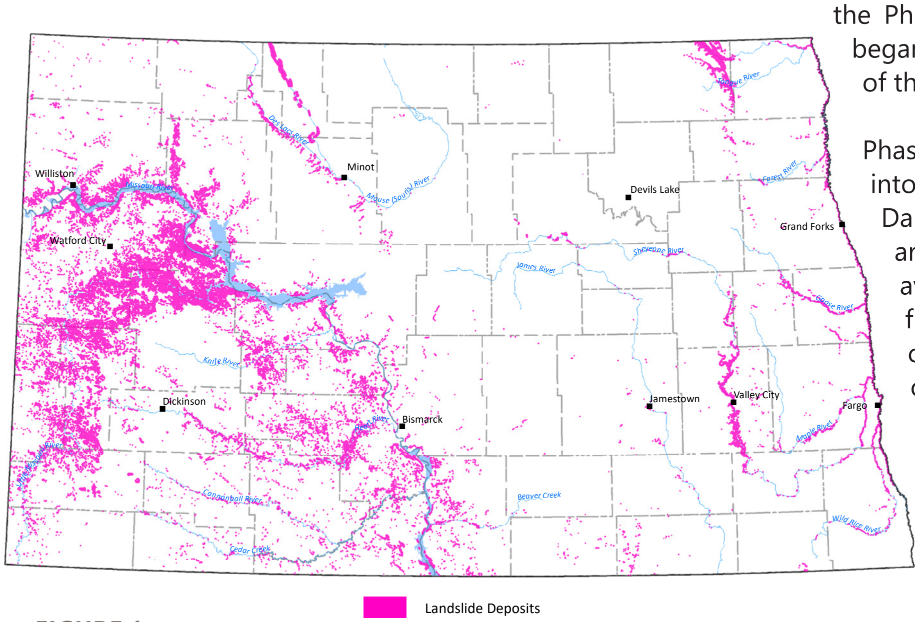

FIGURE 1.
Locations of landslide deposits throughout the state of North Dakota.

Comparing previously mapped Phase II landslides to the newly mapped Phase III landslides can reveal how active or dormant landslides are. This article highlights the 1:24,000 quadrangles that contain new landslides in areas previously free of slope failure as well as failed slopes that have recently become dormant in the Red River and Pembina Gorge areas. Most of the landslides found in these regions are rotational and translational slides, which occur when exposed rocks or sediments fail and move along a curved or planar surface of failure. Visible evidence of these types of slides includes tilted trees or other features rotated along with the rotational block (Schwert, 2003). Though the mechanics are similar, there are other factors that influence landslide development. Flooding in the Red River creates a positive hydraulic pressure and saturates the soil along the river banks. The increased soil moisture in the riverbanks can lead to premature failure (Schwert, 2003). The Pembina Gorge has steeper slopes compared to the Red River Valley which result in more failure prone slopes. As Phase III progresses across the state, new datasets have become available for analysis. This information can be advantageous to city, county, and state planners to know how active slopes are in their area. As mentioned above, LiDAR has been used to identify landslides in North Dakota since 2017. While it is useful to know the location of failure prone areas, it is also useful to know how long an area has been active, or conversely, how long it has been dormant.

This new way to look at the Phase II and Phase III mapping in the state has given us new values to represent the activity of slopes in each respective quadrangle. The first dataset was Phase II landslides by quadrangle in the Red River and Pembina Gorge regions. The second dataset was Phase III landslides in the same quadrangles mentioned previously. From these two datasets, we created two new datasets for a total of four landslide datasets for this comparison: Phase II, Phase III, dormant, and newly active landslides. The remainder of this article will focus on the latter two datasets in more detail.

DORMANT LANDSLIDE AREAS

The dormant landslide area dataset was created by taking the Phase II landslides and removing any overlap by Phase III. The resulting areas represented landslides that were identified as to have occurred before the mapping of Phase II, but have not shown any movement since. Areas that are dormant can indicate where the slopes have stabilized, but can also mean that it should be easier to see signs if the slope has become active again. It is important to note that identified dormant landslides were dormant between Phase II and Phase III mapping (typically an 8–10-year time span). The landslides could have been dormant a day before Phase II mapping, or a hundred years before. Landslide dormancy can be affected by many factors including meander cutoffs/oxbows and preventative efforts such as planting

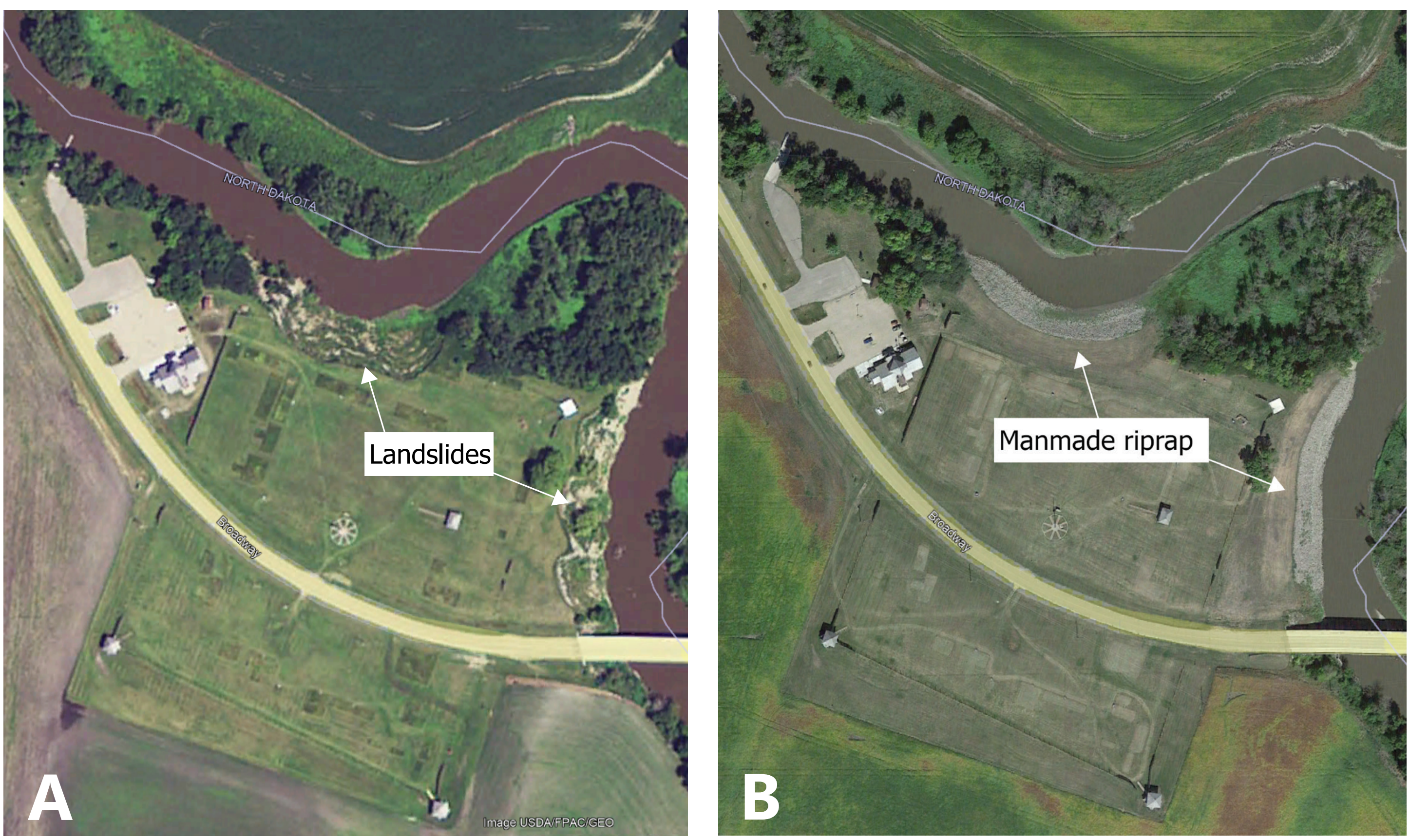

FIGURE 2.
(A) Imagery taken in April 2011 at Fort Abercrombie State Historic Site showing significant landslides approaching the site's structures, and (B) the same location in September 2013 showing landslide mitigation in the form of rock riprap.

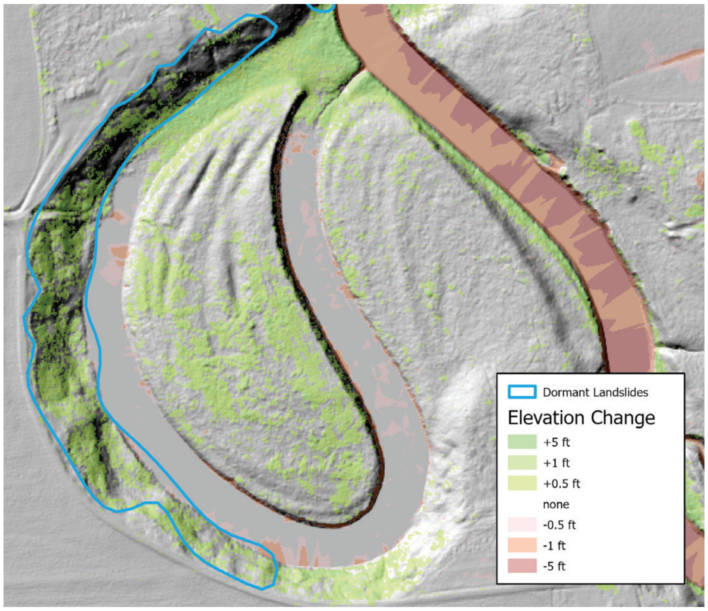

FIGURE 3.
This oxbow lake found south of the town of Oxbow, ND is an example of once active landslides, that once separated from the influence of the river, have become dormant. The blue outline indicates the current dormant landslides.

vegetation or adding riprap as seen at Fort Abercrombie State Historic Site (fig. 2). In the Red River Valley, the Red River and other tributaries can cut off a section of the river and create an oxbow (fig. 3). There is no longer flowing water, except during a flood, and as a result the previously failed landslides along the banks begin to stabilize. In the Pembina Gorge, almost every slope has failed at some point, so much so that entire lengths of slopes along valleys are comprised of previous landslides (fig. 4). Many of the slopes in the Pembina Gorge have stabilized and become dormant as of the time of mapping, while new landslides mapped in Phase III occurred almost exclusively on already failed surfaces (fig. 4).

NEWLY ACTIVE LANDSLIDE AREAS

Like the dormant landslide area dataset, the newly active landslide area dataset was created by taking the Phase III landslides and removing any overlaps with Phase II. The resulting dataset represents landslides that have occurred in areas that had no visible evidence of past landslides. These types of landslides usually occur on the edge of Phase II landslides indicating that the affected area is just expanding rather than entirely new landslides forming. There, landslide expansions comprise most of the newly active landslide area in the Pembina Gorge and the Red River Valley. Occasionally you will see sliding in areas that previously had no failed slope, which is easily picked up on the elevation difference raster mentioned above (fig. 5). Landslides in areas that were historically dormant or stable can take landowners by surprise, cause infrastructure damage, or even force homeowners to move their dwellings.

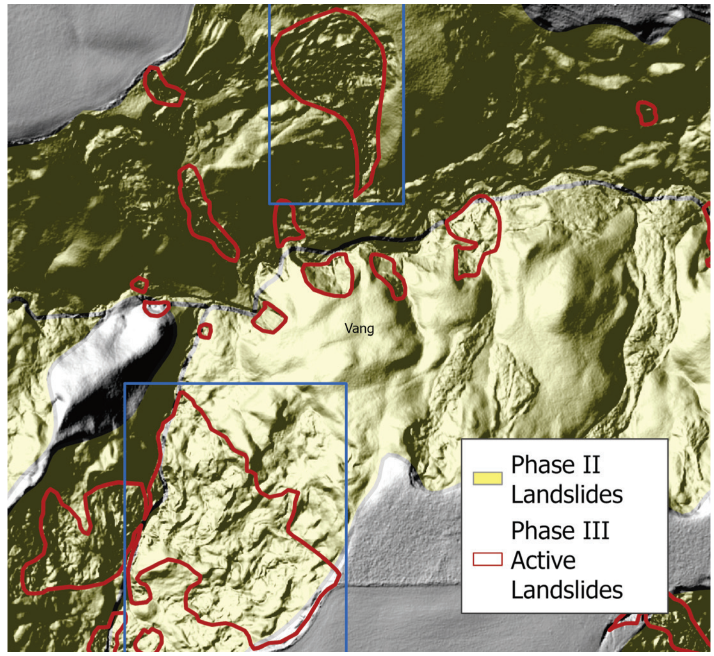

FIGURE 4.
Located in the Pembina Gorge, west of Walhalla, ND, the blue rectangles highlight two examples of active landslides mapped in Phase III that have failed on previously failed slopes. The highlighted landslides look "fresh" with rougher topography that has not smoothed out due to erosion.

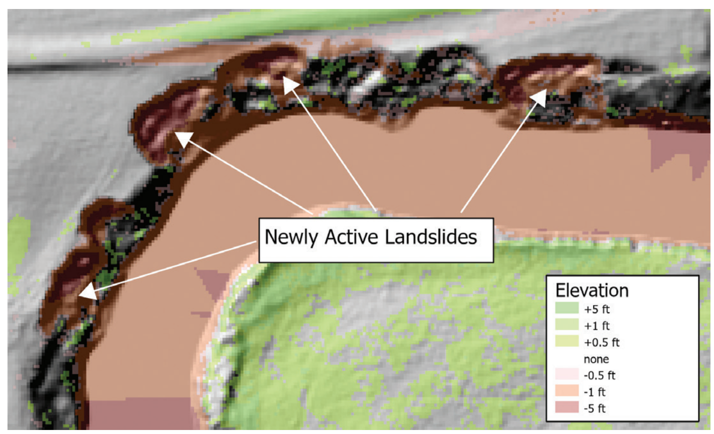

FIGURE 5.
Differential elevation raster overlain on a directional hill shade raster of some landslides north of Abercrombie, ND. The landslides indicated in the image have an iconic concave shape and extend into a previously stable landscape.

LANDSLIDE ACTIVITY

Table 1 demonstrates that most of the previously mapped landslides in the Red River area are dormant. This implies that for at least 8-10 years many of the previously failed slopes have not moved enough to be mapped in Phase III. This is not to say that they will be dormant for the next 8-10 years. Also in Table 1, the overall low number of newly active and high numbers of dormant landslide areas in the quadrangles, indicates that the river meandering may have remained somewhat stable, and the same areas of activity remained active. Likewise, higher active landslide numbers, paired with high dormant landslide numbers, could indicate a shifting in areas of failure, such as meanders getting cut off or landslides occurring on previously stable reaches of the river. It is also interesting to note that the quadrangles with some of the highest dormant area values are near larger cities, which might be explained by the increase of planned slope stabilization and landslide mitigation. In Table 2, which includes the quadrangles for the Pembina Gorge, it is apparent that almost every major slope has failed at some point and now only a few small areas are active, and even fewer areas have newly active landslides occurring on previously stable slopes.

Rivers are a major source of landslides as they are often associated with steeper slopes, and their power to alter the landscape in dramatic ways. Both in the Red River Valley and the Pembina Gorge, most landslides are almost exclusively found along waterways. Landslides can occur gradually or suddenly and take landowners and city planners by surprise. What might have been considered a stable slope along a riverbank might be a dormant landslide that can reactivate at any time when the right conditions are met. As new LiDAR comes out, geologists at the NDGS plan to continually update landslide mapping throughout the State of North Dakota to keep the public well-informed.

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TABLE 1.
Area in square meters for quadrangles that intersect the Red River. The area of the "Dormant landslide area (sq. m)" is calculated by removing the overlap between the Phase II and Phase III landslides and tabulating the area of the remaining Phase II landslides. The "Newly active landslide area (sq. m)" is calculated in a similar way, but instead tabulating the area of Phase III after any Phase II overlap was removed. The two percentage columns are simply the newly tabulated area columns divided by their respective Phase II or III area.

Quadrangle Name	Phase II Landslide Area (Acres)	Phase III Landslide Area (Acres)	Dormant Landslide Area (Acres)	Newly Active Landslide Area (Acres)	% Landslides Remained Dormant
Abercrombie (MN)	35.9	24.6	16.3	5.0	45%
Big Woods (MN)	5.3	4.1	2.4	1.3	46%
Big Woods NE (MN)	1.9	-	1.9	-	100%
Big Woods NW	139.5	95.7	62.9	19.1	45%
Big Woods SW	91.3	119.0	25.6	53.3	28%
Bowesmont	49.2	9.3	39.9	-	81%
Bygland (MN)	372.4	51.7	326.6	5.9	88%
Christine	44.6	23.6	29.8	8.9	67%
Climax (MN)	196.7	99.2	125.2	27.8	64%
Climax NW	357.4	129.0	248.7	20.3	70%
Climax SW	12.0	3.8	10.1	1.9	84%
Drayton	131.1	26.5	110.0	5.5	84%
Dwight	6.4	-	6.4	-	100%
Eldred (MN)	-	0.5	-	0.5	x
Fargo North	289.5	46.5	250.2	7.2	86%
Fargo South	321.0	22.8	305.9	7.7	95%
Georgetown (MN)	436.3	123.4	328.4	15.5	75%
Grand Forks	240.0	70.5	175.6	6.2	73%
Halstad (MN)	231.7	99.3	150.2	17.8	65%
Hickson	197.1	65.8	153.5	22.2	78%
Joliette	143.5	73.8	71.2	1.4	50%
Manvel	6.7	1.0	6.7	1.0	100%
Mattson (MN)	82.4	32.6	52.8	3.0	64%
Oslo	126.2	117.6	40.1	31.5	32%
Oslo NE (MN)	-	2.2	-	2.2	x
Oslo SE (MN)	206.5	89.8	126.4	9.7	61%
Pembina	199.3	45.0	157.1	2.8	79%
Perley (MN)	217.7	55.5	170.5	8.3	78%
Shelly (MN)	185.1	76.7	131.8	23.4	71%
Thompson	34.5	4.8	33.3	3.6	96%
Wahpeton (MN)	-	1.8	-	1.8	x
Wolverton (MN)	10.8	8.7	3.2	1.1	29%

TABLE 2.
Area in square meters for quadrangles in the Pembina Gorge. The area of the "Dormant landslide area (sq. m)" is calculated by removing the overlap between the Phase II and Phase III landslides and tabulating the area of the remaining Phase II landslides. The "Newly active landslide area (sq. m)" is calculated in a similar way, but instead tabulating the area of Phase III after any Phase II overlap was removed. The two percentage columns are simply the newly tabulated area columns divided by their respective Phase II or III area.

Quadrangle Name	Phase II Landslide Area (Acres)	Phase III Landslide Area (Acres)	Dormant Landslide Area (Acres)	Newly Active Landslide Area (Acres)	% Landslides Remained Dormant	% Newly Active Landslides
Hanks Corner	942.2	69.8	885.2	12.9	94%	18%
Olga	3,284.7	503.8	2,861.4	80.5	87%	16%
Olga NW	5,447.8	721.5	4,738.9	12.6	87%	2%
Olga SW	61.0	19.0	55.2	13.2	90%	69%
Vang	7,095.3	796.8	6,353.8	55.3	90%	7%
Walhalla	580.7	161.9	434.3	15.5	75%	10%

NORTH DAKOTA'S SUBSURFACE SALTS

FINDING RENEWED INTEREST FOR POTENTIAL UNDERGROUND STORAGE

www.smithsonianmag.com/innovation/salt-power-plant-most-valuable-180964307

BY TRAVIS D. STOLLDORF

In recent years, subsurface sequestration and storage of greenhouse gas, oil, natural gas, and compressed air has become a global topic of conversation. Sequestering CO_2 to cut greenhouse gas emissions substantially affects North Dakota's coal industry. Propane storage could benefit North Dakota farmers during harvest season when propane use is at its peak. Compressed Air Energy Storage (CAES) could provide emergency electricity during peak hours. All of these factors and others have combined to put a renewed focus on the Williston Basin and, specifically, North Dakota's subsurface salt deposits (fig. 1).

North Dakota has five major salt deposits in the subsurface (fig. 2). The oldest, stratigraphically lowest, thickest, and most laterally extensive salts in the Williston Basin are the Devonian Prairie Formation salts, (Murphy et al., 2009). Although too deep for sequestration or storage potential, the Prairie salt does contain potash (Kruger, 2021), a potassium-rich salt commonly used in fertilizer. The Madison Group's Charles Formation contains six distinct salt packages (Charles A-F salts). Deposited in the Mississippian (Murphy et al., 2009), all but one of the Charles salts are too deep for sequestration or storage potential. The uppermost Charles A (fig. 2) does have potential for underground sequestration and storage due to its shallower depths. The Permian-age Opeche Formation contains Opeche salts A&B (Murphy et al., 2009). The Opeche salts are not potential candidates for underground sequestration or storage due to their high sodium sulfate content which is not suitable for caverns. Later in the Permian, salts of the Pine Member of the Spearfish Formation were deposited in the Williston Basin (Murphy et al., 2009). The Pine salts are laterally extensive, moderately thick, and have potential for sequestration and storage. Lastly, the Dunham salts were deposited in the Jurassic within the Dunham Member of the Piper Formation (Murphy et al., 2009). The Dunham salts are the least laterally extensive of the major salt deposits (Stolldorf, 2021). However, the Dunham Salt holds many advantages over its competition. Dunham salts, when present, typically contain some of the thickest and purest halite in the basin at the shallowest depths below the surface. Thus, the Dunham salts have the highest potential for underground sequestration and storage in the basin.

In light of this renewed interest, the North Dakota Geological Survey (NDGS) has provided industry and the public with detailed summaries, extent, depth and thickness of the Dunham, Pine, and Charles A salts (fig. 3). These salts were chosen as they are all potential underground sequestration or storage prospects.

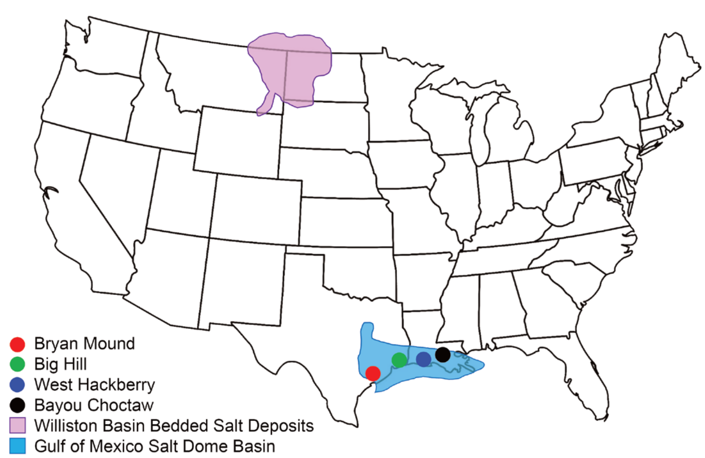

FIGURE 1.
The location of salt deposits in the Williston Basin and the Strategic Petroleum Reserve salt cavern storage complexes. Salt domes along the Gulf coast include the Bryan Mound (red dot), Big Hill (green dot), West Hackberry (blue dot) and Bayou Choctaw (black dot). Figure modified from What is a Salt Dome? (2022).

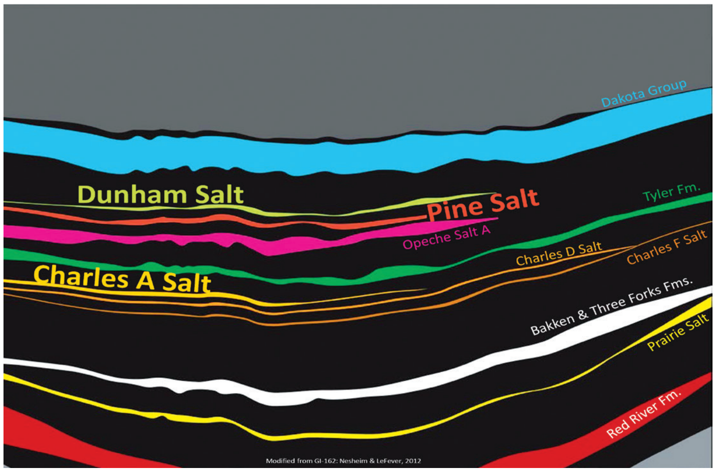

FIGURE 2.
Five major salt deposits lie within North Dakota's portion of the Williston Basin. In order from deepest to shallowest the salts are the Prairie, Charles, Opeche, Pine, and Dunham. The Red River Formation, Bakken-Three Forks Formations, Tyler Formation, and the Dakota Group are added for stratigraphic perspective. Specifically, the Dunham, Pine and Charles A salts are prospective for salt cavern storage. Figure modified from GI-162: Nesheim & LeFever (2012).

SALT CAVERN CREATION AND STORAGE

In order to create a salt cavern, several conditions must be present. The salt formation must be mostly pure with minimal insoluble material such as silt, sand, and clay. Additionally, it must be thick enough and laterally extensive enough to safely create a cavern. Finally, the salt must be within a depth range in which it is stable enough to construct a salt cavern. If all of these conditions are met, a well is drilled into the salt formation and fresh water is pumped into the salt through an independent tubing string. The water solubilizes the salt into a brine which is then removed through a separate tubing string as the cavern forms. A final tubing string provides a fluid blanket, often oil, which prevents erosion of the salt cavern's ceiling. Different circulation methods can alter the shape of the cavern (fig. 4). The direct circulation method, which circulates water through a lower inner tubing string and removes brine from an upper, outer tubing string, produces a consistent oval-shaped cavern. In contrast, the reverse circulation method creates a cavern that is substantially larger at the top than the bottom. This cavern structure is produced by circulating fresh water through the upper, outer tubing string and removing brine through the lower, inner tubing string.

Salt caverns are the preferred locations for storing fluids and gases across the globe due to several advantages. Salt caverns provide the highest flexibility of products that can be stored, from crude oil to compressed air (fig. 5). Due to its physical properties, salt holds pressure without sustaining losses and has no chemical reaction between the salts and the stored fluids or gases (Why Energy Storage, 2022). Salt caverns further provide unmatched deliverability of stored products and rapid cycling of products, going from injection to withdrawal very quickly (Warren, 2016).

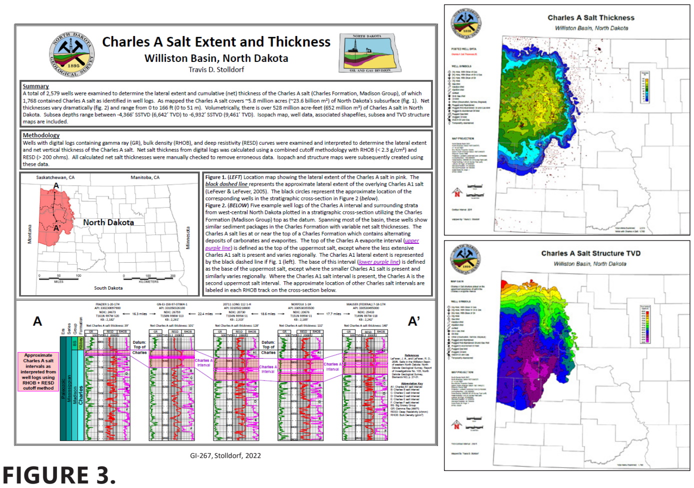

FIGURE 3.
An example of the products available from the North Dakota Geological Survey displaying a summary of the Charles A salt as well as salt thickness maps and structure maps. Similar products are available for the Dunham and Pine salts. Additionally, shapefiles are available for isopach and structure contours as well as well data. Figure from GI-267, Stolldorf (2022).

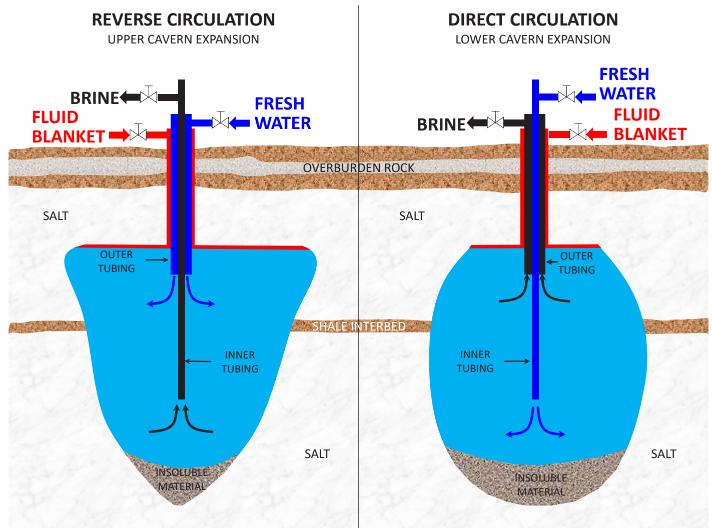

FIGURE 4.
Salt caverns are created by injecting water into salt, removing the resulting brine and replacing this void with other fluids or gases. The example on the right is direct circulation in which fresh water is injected into the lower portions of the cavern through the lower, inner tubing string and brine is removed through an upper, outer tubing string. The opposite is true for the reverse circulation method (left) where fresh water is injected through the upper, outer tubing string and brine is removed through the lower, inner tubing string. The reverse circulation method forms a cavern that is larger at the top than at its base. A fluid blanket (typically oil) is also necessary to prevent erosion of the cavern's ceiling.

STORAGE WITHIN SALT CAVERNS

Canada was the first North American country to use salt caverns for underground storage, using caverns to store oil during WWII. In 1949, the U.S. first stored liquified petroleum gas in Permian salts in Texas (Warren, 2016). In North Dakota, the Dakota Chemical Company constructed a plant in 1959 near Williston to mine the Charles salt and later planned to use the caverns for liquified petroleum gas (LPG) storage (UIC Permit, 1985). However, it could not be verified that any LPG was ever stored at the facility.

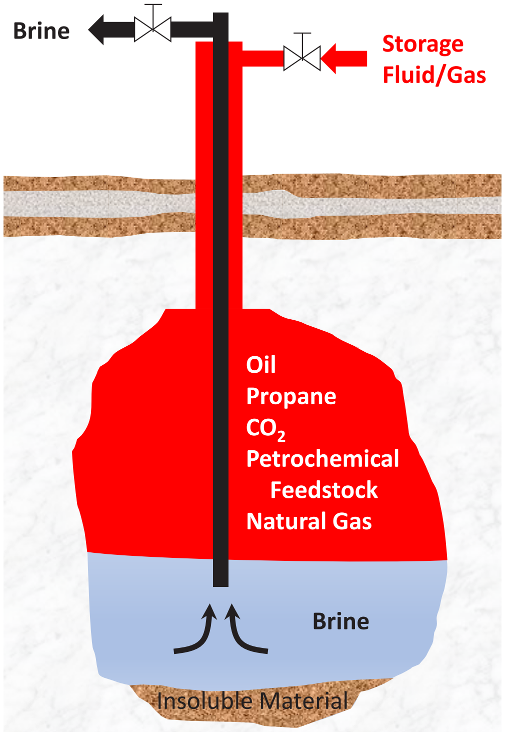

FIGURE 5.
Salt caverns offer higher deliverability and rapid cycling of a variety of fluids and gases. Oil, natural gases such as propane, and compressed air can be stored in salt caverns. Brine is removed as the storage fluid/gas is added. The reverse is true when removing the stored fluid/gas.

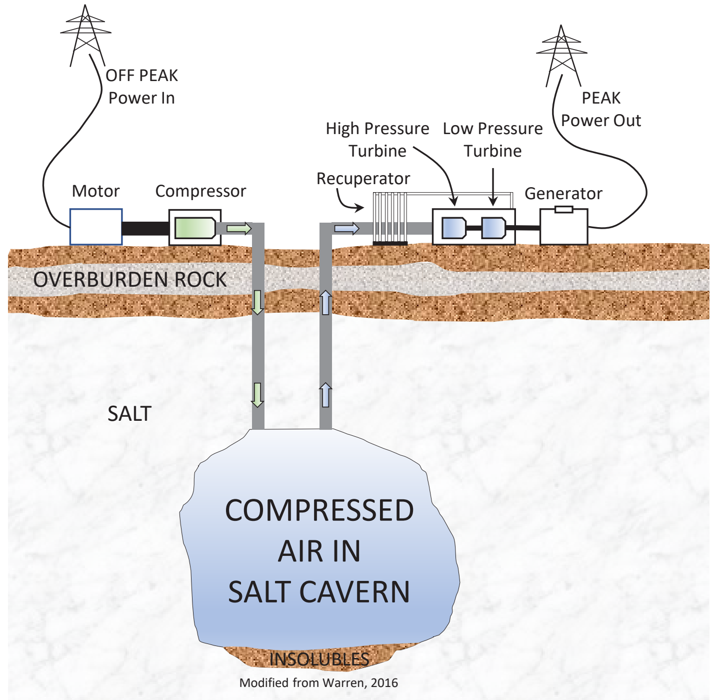

FIGURE 6.
Compress Air Energy Storage is a system in which air is compressed and injected into a salt cavern for temporary storage. The compressed air is released from the cavern and sent through conventional gas turbines which in turn power a generator that produces emergency electricity. Figure modified from Warren (2016).

Until the oil shocks of the 1970s, salt cavern storage had mainly been utilized by the petrochemical industry (Strategic Petroleum Reserve, 2022).

However, in 1975, Congress enacted the law that created the Strategic Petroleum Reserve (SPR) to diminish the impact of global supply disruptions and provide necessary reserves to the United States (Warren, 2016). The SPR is one of the most well-known salt cavern storage systems in the U.S. and today, the SPR is being talked about much more in light of recent world events. The SPR is the world's largest supply of emergency crude oil and, as of the end of 2021, the SPR held nearly 600 million barrels of oil, or the equivalent of over 3 years of petroleum imports (SPR, 2022). This crude oil is stored in four main salt cavern complexes located along the Gulf Coast (fig. 1) with two sites located in Texas (Bryan Mound and Big Hill) and two sites in Louisiana (Bayou Choctaw and West Hackberry). These locations were selected based on their proximity to large salt deposits along the Gulf Coast (fig. 1) and crude oil distribution pipelines. The four main complexes are made up of 60 individual salt caverns. Caverns vary in shape and size but are generally cylindrical and have an average diameter of 200 feet with a height of 2,550 feet (SPR, 2022).

Compress Air Energy Storage (CAES) is another way salt caverns are being utilized. CAES is a system where compressed air is injected into a salt cavern for storage (fig. 6). During peak electricity usage, the compressed air is released from the cavern and sent through conventional gas turbines which in turn power a generator that produces emergency electricity (Warren, 2016). In 1978, Germany was the first to use salt caverns for CAES. In 1991, the U.S. followed suit by creating the first CAES in North America near McIntosh, Alabama (Warren, 2016).

The various salt formations within North Dakota's subsurface have yet to be utilized for salt cavern development and storage. However, recent mapping completed by the NDGS adds valuable geologic information to future development as salt cavern storage may play an important role in North Dakota's economic future.

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OLD DATA FINDS NEW INTEREST

BY NED W. KRUGER

INTRODUCTION

Commodity cycles for uranium oxide, commonly known as yellow cake, have resulted in periodic waves of exploration interest in North Dakota. The first cycle which led to uranium exploration in the state occurred in the late 1950s, and uranium was produced from 1962-1967 in mines located both north and south of the town of Belfield. One of these mines was the Fritz (or Church) Mine, located first in Billings County and later also producing in Slope County (fig. 1). Nine years after uranium mining ceased in North Dakota, increased commodity prices generated a new round of uranium exploration between 1976 and 1980. At that time, most of the exploration took place between the towns of Belfield and Fairfield as well as the Chalky Buttes area south of Amidon. The uranium was found in coals and sandstones of the Sentinel Butte Formation. The price of uranium began another upcycle in 2004 as stockpiles of uranium decreased around the world (Murphy, 2008). Prices peaked at $136 per pound in June of 2007, sparking a renewed interest in North Dakota's uranium deposits.

The North Dakota Geological Survey (NDGS) issued two permits in May of 2008 to Formation Resources, Inc. to explore for uranium in southeastern Billings and northern Slope counties. The basic data generated from the exploration activities under these permits was submitted to the NDGS, where the information has been archived. This information is available to the public since there is no longer an active mining interest being pursued by Formation Resources, Inc.

BASIC DATA

Formation Resources, Inc. primarily targeted two, near-surface coals ranging in thickness from 1 to 16 feet (0.3 to 4.9m) in the vicinity of the old Fritz Mine (Murphy, 2009) (figs. 1 and 2). They analyzed these coals for uranium and its associated metals; molybdenum, germanium, and arsenic.

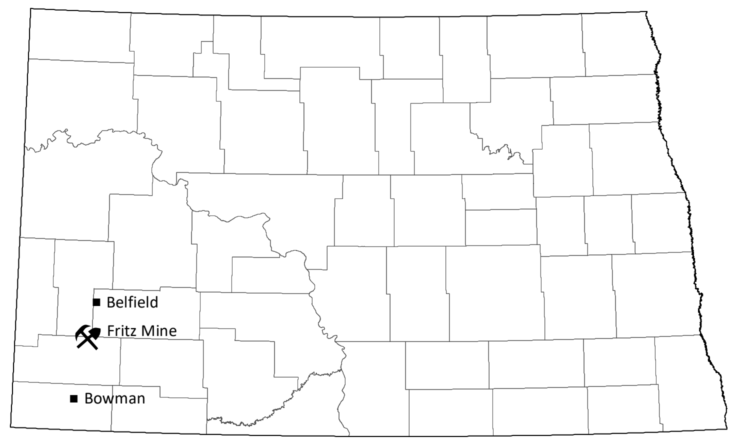

FIGURE 1.
State map showing the location of the old Fritz Mine in relation to the towns of Belfield and Bowman.

Formation Resources drilled 400 boreholes ranging from 8 to 205 feet (2.4 to 62.5 m) in depth, excavated several dozen trenches, and analyzed 1,788 core and trench samples (table 1). In addition, they took 2,113 field radiation measurements.

The vast amount of data that Formation Resources collected in a relatively small area provides important insight into the lateral and vertical variability of mineralized lignite in North Dakota. This is especially true for germanium, which is one of the critical minerals that we have been pursuing in our critical mineral project in western North Dakota. The average concentration of germanium from the Formation Resources exploration program (28.6 ppm) is twice that of a typical North Dakota lignite (14 ppm) based on the NDGS's more widely distributed sampling efforts (see figure 1 on page 2 of this publication to see sampling locations to date in the western North Dakota study; Moxness, 2022). As can be expected from an area known to be enriched in uranium, Formation Resources' average concentrations of uranium (337 ppm),

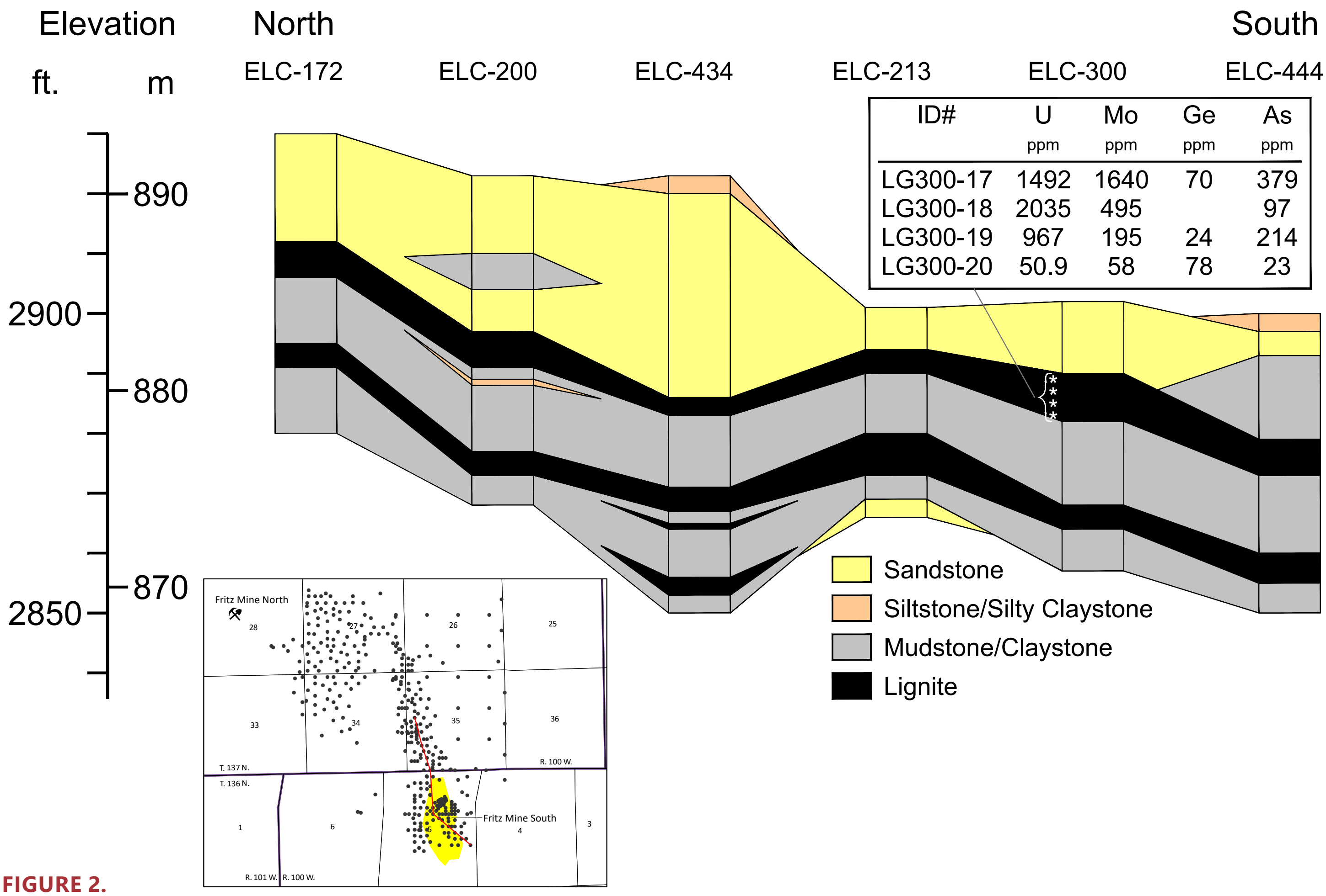

FIGURE 2.
Cross-sectional representation of the stratigraphy from six boreholes in the southern portion of Formation Resources, Inc.'s study area. Section position is displayed as the red line in the inset. An example of laboratory measurements for uranium, molybdenum, germanium, and arsenic are given for four samples collected at one foot intervals in one of the coals.

TABLE 1.
Analytical statistics comprised of maximum, minimum, mean, and median concentrations of uranium, molybdenum, germanium, and arsenic from core samples and trench samples.

Drillhole and trench assays:	U (ppm)	Mo (ppm)	Ge (ppm)	As (ppm)
# samples:	1,650	1,649	1,609	1,650
Max:	48,000	19,896	188	3,580
Minimum:	< 4	< 2.5	< 5	0.48
Mean:	337	212	28.6	128
Median:	17.0	16.0	< 5	28.5

molybdenum (212 ppm), and arsenic (128 ppm) also exceed the averages of a more typical lignite (17, 29, and 75 ppm, respectively, based on the NDGS data). We visited this area of known mineralization in 2017 to investigate if rare earth elements might also be enriched alongside uranium in these lignites (Kruger et al, 2017). The 31 NDGS samples from nine measured sections in and adjacent to the old Fritz mines contributed to a growing dataset suggesting rare earths are not closely correlated, but with such high concentrations of other elements, the Formation Resources' dataset is noteworthy regardless, and serves as the best example of a well-characterized uraniferous deposit in North Dakota.

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

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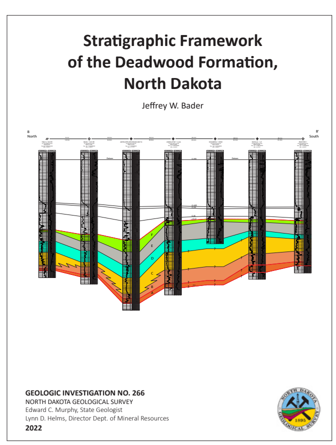

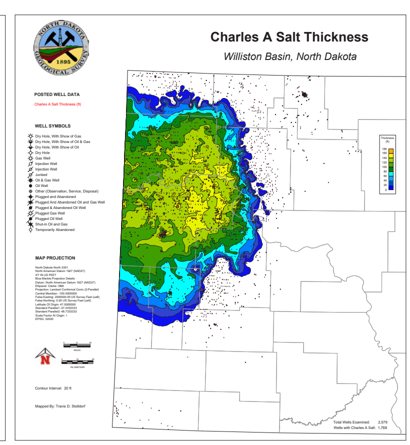

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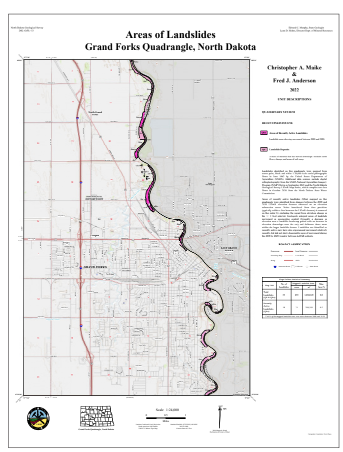

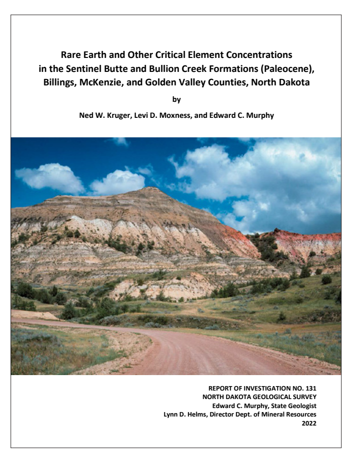

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