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FEATURES

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ON THE COVER:
Reconstruction of *Jormungandr walhallaensis* shown engaging in intraspecific combat. Illustration by Henry Sharpe.

NORTH DAKOTA'S MOSASAUR

BY CLINT A. BOYD

October is a time of ghosts and ghouls, costumed creatures, and malevolent monsters. This year the paleontology team at the North Dakota Geological Survey fully embraced the spirit of Halloween, introducing the world to a never-before-seen sea monster that terrorized the Western Interior Seaway of North Dakota 80 million years ago during the Cretaceous Period. On October 30th, after eight years of hard work, a new species of mosasaur that first emerged from the black shale of the Pembina Gorge in 2015 was named: *Jormungandr walhallaensis* (Zietlow et al., 2023).

AN IMPORTANT TRANSITIONAL SPECIES

Mosasaurs were aquatic reptiles that lived mostly in marine environments during the Cretaceous Period, including the Western Interior Seaway that once covered most of North Dakota. They were the apex predators of their time, with some reaching lengths in excess of 40 feet. The specimen recovered from the Pembina Gorge was from an animal approximately 24 feet in length, which is still an impressive-sized animal (see cover image). They were fully adapted to their aquatic lifestyle, with large flippers on the front and hind legs and most species likely had a fluke on the tail. However, like modern whales and other aquatic mammals, they had to return to the surface in order to breathe. They had finely patterned scaly skin and likely did not lay eggs like many other reptiles; instead, they gave birth to live young in the open ocean (Field et al., 2015).

We previously reported on the discovery of this new species of mosasaur and the initial fieldwork focused on recovering the animal in a newsletter article in January 2017 (Boyd, 2017). It was clear at that time that the partial skeleton that was discovered in 2015 was a new species, but at that point, only a small portion of the specimen was fully cleaned. As work on the specimen progressed over the years, it became clear to us that this specimen was more unique than we originally suspected. In the 2017 article, I suggested it may represent a new species of the genus *Mosasaurus*, but as additional bones were exposed it became clear this specimen didn't conform with any currently described genus. The quadrate, which forms the outer portion of the ear and the jaw joint, closely resembles *Mosasaurus*, but the jaws and the skull roof more closely resemble the smaller and slightly older genus *Clidastes*. We had a bit of a conundrum on our hands!

FIGURE 1.
Photograph of the first Public Fossil Dig event in August of 2000 in the Pembina Gorge State Recreation Area. Participants are working along a continuous fossil layer in the Pierre Formation immediately adjacent to the road.

FIGURE 2.
NDGS paleontologists Clint Boyd (left), Becky Barnes (middle), and Jeff Person (right) removing plaster jackets containing the skull of the newly named mosasaur *Jormungandr walhallaensis* during the Public Fossil Dig in the Pembina Gorge State Recreation Area in 2015. Note the position of the quarry above the road surface (upper left). Photograph by Sean Ternes.

To help solve this riddle, we brought in two outside researchers with extensive knowledge of mosasaur anatomy and relationships: Amelia Zietlow and Nathan Van Vranken. Nathan is a member of the faculty at Eastern West Virginia Community and Technical College and has worked with our team previously to describe the first mosasaur fossils collected from the Breien Member of the Hell Creek Formation in North Dakota (Van Vranken and Boyd, 2021). Amelia is a student studying mosasaurs at the Richard Gilder Graduate School at the American Museum of Natural History. Together, we set to work examining the new mosasaur's bones and comparing them to known species. After months of research, it was clear that this new species was indeed intermediate between *Mosasaurus* and *Clidastes*, providing new information on the evolution of these mosasaurs. The transitional nature of this specimen fits with the age of the specimen, which comes from the middle Campanian (~80 mya) Pembina Member of the Pierre Shale Formation. *Clidastes* is most commonly recovered from older rocks, and last appears in the middle Campanian. Alternatively, Mosasaurus first appears in the upper Campanian and persists into the Maastrichtian, going extinct at the end of the Cretaceous Period.

CONSTRUCTING THE NAME

Species names have two parts that are always used together. The first word is the name of the genus, and the second word is the species epithet. For example, in the dinosaur *Tyrannosaurus rex*, *Tyrannosaurus* is the genus and rex is the species epithet. Very early in my work on this specimen, I decided that if it was a new species the species epithet should reflect the region it came from in North Dakota. When we are conducting fieldwork in the Pembina Gorge each summer we stay in the city of Walhalla, and we have grown very fond of the area and the people that live there. So, I decided the species epithet should honor the city. When you form a species epithet in reference to a geographic location you add the suffix -ensis at the end of the name, so a species named after Walhalla becomes walhallaensis. As research on the specimen continued and it became clear that it represented a new genus as well, I tried to think of a name that would work well with the species name. Given the similarity of spelling between Walhalla and the mythological Norse location Valhalla, we chose to name it after the legendary sea-dwelling World Serpent: *Jormungandr*. The resulting name, *Jormungandr walhallaensis*, honors both the region in which it was discovered and the Scandinavian heritage of many who currently call the area home.

IMPORTANCE OF EXCAVATION

This discovery highlights the importance of the work done by NDGS paleontologists to protect and preserve North Dakota's prehistoric heritage, often through our Public Fossil Digs program. The first ever NDGS public fossil dig was held in the Pembina Gorge in 2000 in the same area where this new mosasaur would eventually be discovered (fig. 1). That work was prompted by the need to continually cut back the uphill slope along an important road running through the Pembina Gorge State Recreation Area. Throughout the Pembina Gorge, the soft rocks of the Pierre Formation are steadily eroding and slumping off the steep walls of the gorge and into the river below. As a result, the road at this location must be moved over a few feet every few years as the rock beneath it slumps away. These actively eroding hillsides are great places to find fossils, and at the site of our fossil dig there are an exceptionally high number of fossils present. These fossils would quickly be lost, either to natural erosion or to construction work on the road, if we were not actively working to collect and preserve them. As a result, our work in the Pembina Gorge is a constant race to discover and remove all the fossils we can each summer so that the road can remain open.

When we first started work on this specimen in 2015, the location that would eventually become the *Jormungandr* quarry was about 15 feet off of the road and 15-20 feet above the road surface (fig. 2). We actively worked that quarry from 2015 through 2018, when we recovered the last of the specimen and moved to another location on the

FIGURE 3.
Panoramic photograph of the outcrop of the Pierre Formation along the newly rebuilt road through the Pembina Gorge State Recreation Area shortly after construction was completed. The white dashed line highlights the current position of the old back wall of the quarry where *Jormungandr walhallaensis* was collected. Photograph by Clint Boyd.

hillside. Over the years the rocks in this area have slid down so that the quarry is now only about 10 feet or so above the road. In the summer of 2022, a large area of rock downslope from the road failed and slumped away, requiring the road to be closed until work could be completed to remove several feet of the rock uphill from the road and shift the entire road surface over away from the edge of the gorge. The required work was so extensive that the entirety of the hillside where the quarry was located was removed, with only the very back wall of the quarry now visible (fig. 3). If we had not discovered this specimen years earlier and had the time to fully collect it, this scientifically important specimen would have been lost over the side of the hill during this construction work. This is the exact reason why we return to the Pembina Gorge each summer to scour this hillside for fossils: every discovery is time-sensitive and needs to be acted on immediately or be lost forever.

REBUILDING A SEA MONSTER

This mosasaur specimen provided a unique opportunity to understand mosasaur anatomy. Many mosasaur specimens are found with their skull bones still connected in life position, often squashed or flattened into a single layer. In those cases, only some of the bone surfaces can be observed, while others are covered or completely obscured by other bones. The skull of *Jormungandr* is preserved disarticulated, with nearly all of the skull bones separated from the others, allowing all surfaces to be examined. We quickly realized that this style of preservation provided us with a unique opportunity to produce a detailed, fully figured description of mosasaur skull bones that would be extremely helpful to other researchers in identifying mosasaur bones from other sites. But as we moved forward with our work on the specimen, we quickly encountered a few problems.

The first problem is that the bones are bright white in color and are fossilized in part by reflective gypsum minerals, making them difficult to properly photograph. Second, many of the bones have deep folds and grooves, making it difficult to get the entire bone surface into focus in a single image. The final, and biggest, problem is that the bones are very fragile, making them difficult to handle or position in the correct view without damaging them. The solution to these problems was to employ a high-tech solution: 3D scanning. Using an Einscan-SP scanner and an automated turn table, we were able to produce 3D models of every bone we have from Jormungandr. Once a model of a bone was finished, it could be rotated and artificially lit in any view we needed to figure with no risk of harm to the fossil (fig. 4).

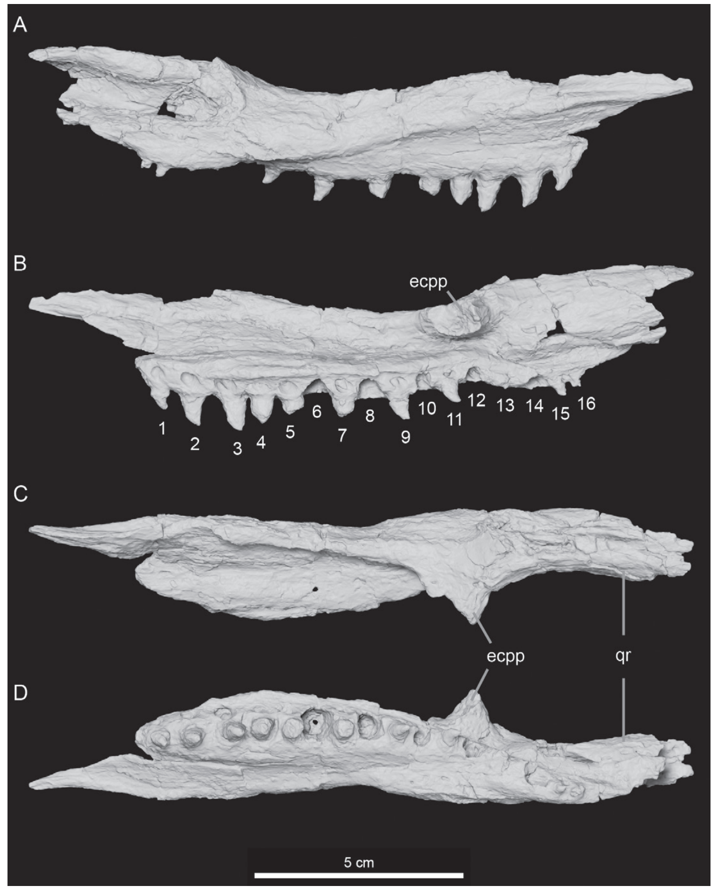

FIGURE 4.
3D model of the left pterygoid of NDGS 10838, the holotype of *Jormungandr walhallaensis*, shown in medial **(A)**, lateral **(B)**, dorsal **(C)**, and ventral **(D)** views. In **(B)**, tooth positions are numbered. Abbreviations: ecpp, ectopterygoid process; qr, quadratic ramus. Figure modified from Zietlow et al. (2023: fig. 28).

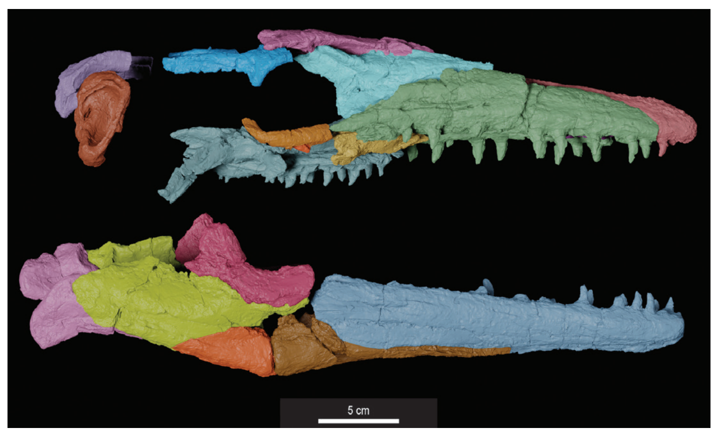

FIGURE 5.
Reconstructed model of the skull of *Jormungandr walhallaensis* shown in right lateral view. The skull was digitally assembled using 3D scans of the real bones. Any bones not preserved in this specimen are not present in this reconstruction. Model constructed by Amelia Zietlow.

Another benefit of scanning all of the bones is that we could load them all into a program and reassemble them into life position, producing an accurate model of how Jormungandr's skull would have looked in life. In cases where we only had a bone from one side of the skull preserved, we were able to mirror image the model and use it to replace the missing bone on the other side. Using those methods, lead author Amelia Zietlow was able to reconstruct most of the skull; however, some portions of the skull, including the braincase, were completely missing from the specimen (fig. 5). To address that problem, we partnered with paleontological exhibits company Triebold Paleontology Inc. They had models of the bones we were missing from closely related mosasaur species

FIGURE 6.
3D printed cast of the reconstructed skull of *Jormungandr walhallaensis* shown in right lateral view. Triebold Paleontology Inc. filled in any missing bones using data from closely related species, printed the finished model on a resin printer, painted the cast to match the color and texture of the original bones, and built the metal armature to hold the specimen. This skull is now on display at the Walhalla Public Library. Photograph by Clint Boyd.

that they used to fill in the rest of the skull, completing the model. They then 3D printed the skull on a large format resin printer and painted it to resemble the original fossils (fig. 6).

NEW EXHIBIT

Once our research was finished and we had confirmed that the Pembina Mosasaur is a new species, we wanted to set up an exhibit in the local area so that people in that area could learn about the unique mosasaur that is currently only known from the rocks exposed in the Pembina Gorge. Our work in that area is based out of the town of Walhalla, and we already have an exhibit in the Walhalla Public Library that includes the first mosasaur fossils the North Dakota Geological Survey collected from the Pembina Gorge over 20 years ago. We talked with the librarians and came up with a plan to commission a cartoon-styled mural for the children's area of the library (fig. 7) and provide a cast of Jormungandr's skull, along with casts of other fossils found in the Pembina Gorge. The casts were delivered to the library in June, but installation of the mural was delayed while some repair work was done on the ceiling in the area where it will be installed. This new exhibit adds to our array of over two dozen fossil exhibits across North Dakota that represent our commitment to exhibiting the best fossils North Dakota has to offer in the local area whenever possible (Barnes and Boyd, 2022).

MORE YET TO COME

The publication of *Jormungandr walhallaensis* is the culmination of a lot of work by paleontologists here at the North Dakota Geological Survey and the outside researchers that collaborated in this study. The result is the first new mosasaur species named from North Dakota, providing recognition of the rich fossil record of these animals preserved in our state. But while *Jormungandr* is North Dakota's first named mosasaur, it is unlikely to be the last. The well-preserved mosasaur skeleton previously collected outside of Cooperstown in Griggs County (Hoganson et al., 1996) and an impressively large mosasaur skeleton collected near McCanna in Grand Forks County (Hoganson, 2014) are currently under study and either, or both, may represent previously unknown species. Additionally, we have multiple other mosasaur specimens from the Pembina Gorge that are clearly not the same species as *Jormungandr walhallaensis* that we are working to identify. Thus, the description of *Jormungandr walhallaensis* marks the very beginning of our work on North Dakota's mosasaurs.

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FIGURE 7.
Mural created for the Walhalla Public Library for the new exhibit installed in the kids' reading area depicting a cartoon version of the fauna of the Western Interior Seaway as preserved in the Pierre Formation that crops out in the local area. The mosasaur *Jormungandr walhallaensis* is the centerpiece of the mural. Art by Karolina Twardosz.

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

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Take a prehistoric fishing trip to the northeastern corner of the State, in the beautifully scenic Pembina Gorge. 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.

Or if getting out and hiking is more your style, check out the Dickinson Area site inside the Little Badlands of North Dakota. These 32-30-million-year-old Oligocene rocks hold micro-mammals galore, monstrous rhinos and entelodonts, and pint-sized horses, deer, camels, cats, and bats.

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 2-Day Site Closing Session may finish early on the 2nd 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.
- No personal vehicles! All participants will be transported by van from the meeting site to the dig site.

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

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GETTING INTO...
HOT WATER

BY NED W. KRUGER

INTRODUCTION

A drilling derrick juts up from amongst the harvested prairie fields in the northern portion of the Williston Basin. Its drill bit has sunk 10,000 feet (3,050 m) into the underground rock formations and will soon kick off from vertical and continue onward in a horizontal leg to the west. Highly skilled oil and gas workers perform their tasks with precision, grateful for this opportunity to work. It's the fall of 2020, and elsewhere drill crews are being idled as a glut of oil takes shape due to the sudden drop in economic activity across the globe, but this crew is not targeting a bench of the Bakken, in fact, they are not drilling for crude oil at all. They are drilling for water from a deep, hot aquifer at the base of the sedimentary basin, to mine its heat.

ADDING RENEWABLE ENERGY TO THE GRID

The company behind the project, DEEP Earth Energy Production Corp. (DEEP), was formed in 2010 and undertook its first drilling and testing phase in 2018, southwest of Estevan, Saskatchewan, and only 2 miles (3.2 km) from the border of North Dakota. Initially, their vision was to develop geothermal power facilities capable of supplying 100 to 200 megawatts of power from a series of small, repeatable 5-10 megawatt (MW) plants. The water comes from the Deadwood Formation, sitting atop the Precambrian basement, as well as the Winnipeg Formation (U.S. equivalent Black Island Formation) with the overlying Icebox Formation acting as a caprock and heat insulator (Zinchuk, 2018). Their testing has recorded water temperatures up to 261°F (127°C) from this aquifer. With the deepest portion of the Williston Basin located in North Dakota, even higher water temperatures can be expected in the state. The NDGS has recorded temperatures of 297 and 299°F (147 and 148°C) at depths of approximately 13,000 feet (3,962 m) within the Interlake and Stony Mountain Formations, respectively, in McKenzie County (McDonald, 2015). These temperatures were obtained 1,700 to 1,800 feet (518 to 549 m) above the Deadwood Formation at those locations.

Like wind, solar, and hydroelectric power generation, geothermal energy is renewable and produces zero emissions. Unlike other renewables, apart from hydroelectric, geothermal provides reliable baseload power, meaning it can generate and send power to the electric grid 24 hours a day. It also has a smaller surface footprint and does not interfere with wildlife migration patterns. While initial costs of construction are higher for geothermal energy facilities, over time they are competitive, with lower operating and maintenance costs.

The plant will operate using an Organic Rankine Cycle generator. Production wells will bring geothermal fluid up to pass through a heat exchanger where heat is transferred to a working fluid, like butane, which vaporizes, expands, and turns a power-generating turbine. The working fluid, contained in a closed loop, condenses as it cools and is re-used. The geothermal fluid is injected back into the aquifer to maintain pressure while absorbing more heat from the sandstone it passes through on a slow route back toward the production well (fig. 1).

Testing of this aquifer has shown much of the produced brine is sourced from a fractured reservoir system. Hydraulic stimulation and production modeling indicate commercial production rates of 26.5 gallons (100 liters) per second can be sustained. According to DEEP, the main constraints to production and injection rates are well design and pump size (Deep Corp., 2020).

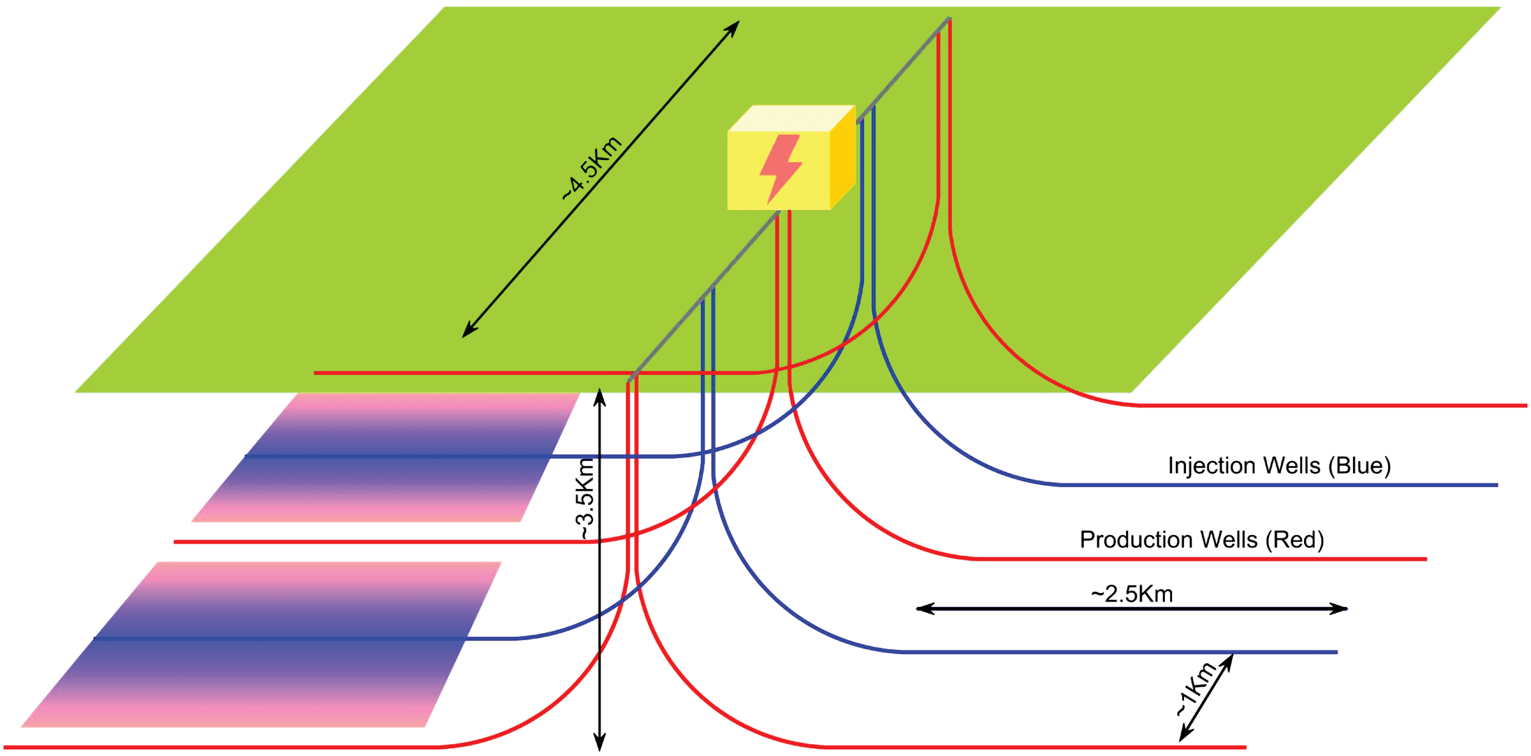

FIGURE 1.
Illustration of a preliminary design of a 10-well, 20 MW plant, modified from RESPEC. The horizontal wells on the left show injected water gaining heat as it percolates through the rock toward the production wells. New designs for a higher-capacity plant include more wells with longer lateral sections.

The flow rates observed thus far have led DEEP to increase their plant energy output estimates from 5-10 MW to 35 MW using 34 horizontal wells – consisting of 18 production and 16 injection wells. The subsurface development will be drilled and completed at the surface facility location along with four additional drilling pads and is planned to begin operation in early 2025. This would be stage one of an envisioned four-stage build of 35 MW plants, a scale-up that would provide 140 MW of power to the Canadian energy grid (Pipeline Online, 2022). Thirty-five MW is roughly the amount of energy needed to supply 35,000 homes and 140 MW would supply 140,000 homes.

There are also some potential synergies to be found. Regional waste flare gas could be captured and used to help power the plant's parasitic load, the energy draw required by the geothermal facility itself which would otherwise cut into the amount of energy supplied to the grid. Left-over heat in the water, approximately 149°F (65°C) as it exits the heat exchanger, could be used for greenhouses or other applications. Before injection back into the aquifer, this water could also be processed for rare earth and other critical mineral extraction, inviting the potential for partnerships with other mineral development companies.

Early on, the project received $175,000 from the government of Saskatchewan and another $1.3 million from Natural Resources Canada, put toward test drilling, to increase the percentage of renewable-sourced energy in the province's overall power supply. There was also an early power purchase agreement signed with SaskPower which helped attract private investments. Subsequently, the Government of Canada announced $25.6 million in funding for the plant in 2019. If successfully implemented, this work will move SaskPower closer to its goal of 50% renewable power generation by 2030.

There was an interesting, symbiotic dynamic between geothermal and oil and gas development which occurred at the early stages of DEEP's drilling and testing in 2020. In the face of a historic oil and gas downturn, DEEP was able to use equipment and employ crews that may have otherwise left the service sector and region, keeping them available for when the oil and gas climate returned to normal. DEEP CEO Kirsten Marcia, having many years of experience in the oil and gas industry, gives that industry due credit. She notes that DEEP is using oilfield data, technology, and processes to establish a renewable resource, which absent the industry, would not even be known to exist.

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A THUMP IN THE NIGHT

REPORTS OF POSSIBLE Cryoseismic Occurrences in North Dakota

BY FRED J. ANDERSON

Most of us are aware that earthquakes are a dynamic Earth process and have the potential, in certain areas of the country, to cause significant damage and loss of life. Fortunately, North Dakota is in the most seismically quiet portion of North America, where only minor earthquakes occur relatively infrequently. Minor, low-magnitude earthquakes, that are commonly only detectable by seismic instrumentation, with local magnitudes of around M 3.0, have occurred somewhat infrequently in North Dakota about once a decade (Anderson, 2016).

Over the past twenty years that I have been with the North Dakota Geological Survey in Bismarck, I have served as the resident seismologist (when needed) in addition to my regular day to day geologic duties as an applied geologist investigating our state's geologic resources and creating geologic maps. One of the many additional duties of a Survey geologist, is to respond to public inquiries and geologic information requests from our residents. Occasionally, we receive some interesting and sometimes colorful calls from people reporting things such as unexplained bright lights in the night, possibly witnessing a meteor shower with an associated meteorite fall, and infrequent unexplained loud noises and sounds like loud cracks and booms from the field and farm. Occasionally, we receive a report of a perceived earthquake occurrence, some of which have been rather interesting and somewhat entertaining.

Commonly, with these types of reports, further investigation shows no indications of recorded seismicity on regional seismographs. At first these reports were just taken as anomalous possible earthquake reports but when these reports are considered collectively, they are found to have many of the reported characteristics of cryoseisms, which are small non-tectonic earthquakes caused by freezing action in ice, ice-soil, and ice-rock materials (Lacroix, 1980).

A cryoseism can occur when the outside air temperature drops suddenly, causing rapid freezing within the frost zone or areas with permeable soils that contain shallow groundwater and within ice itself such as in a freezing river, lake, or pond (fig. 1). Since the expansion of water due to freezing can be up to 9% by volume, it is this rapid expansion that causes acute fracturing within the frozen ground or ice mass creating cracking noises often described as loud "booms" or sounds like thunder (fig. 2).

One of the more interesting public reports that we have received somewhat recently (Table 1) occurred during the midnight hours of December 04, 2018 when a trailer-home resident from Tioga reported that "it felt like my trailer house was wobbling like it does when my clothes dryer is spinning".

Considering this as a possible earthquake report, a review of regional seismic station data showed no seismic activity occurring during the reported period. However, this type of report is somewhat consistent with that of a cryoseism.

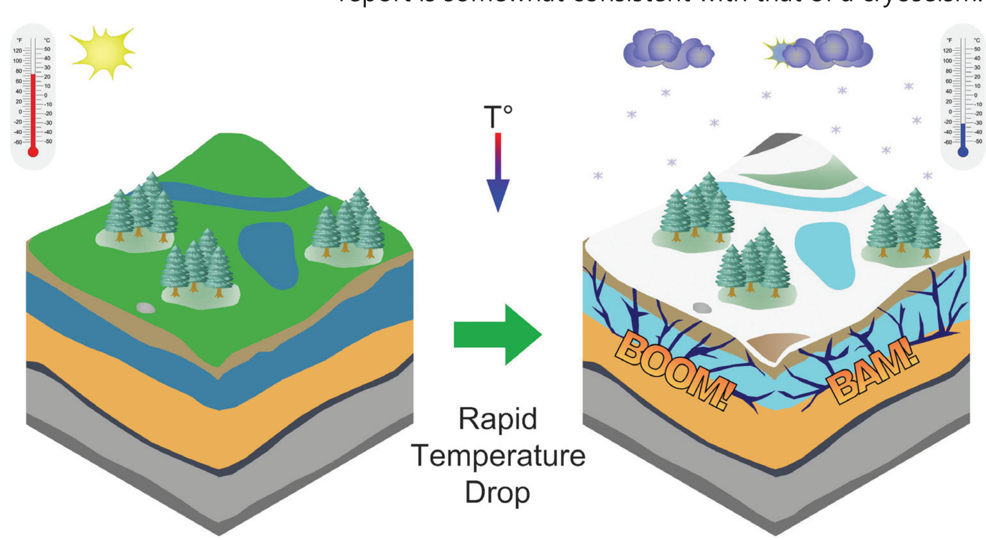

FIGURE 1.
Block diagram illustrating some of the common features associated with cryoseisms such as rapidly freezing saturated permeable soils, lakes, and streams.

FIGURE 2. Ice-jam on the Missouri River at the Double Ditch Indian Villiage State Historic Site during late March in 2009. Buckling and grinding slabs of ice can be noisy creating sounds like creaking, twangs, and booms.

The characteristics of Cryoseisms fall into three categories: meteorologic, geologic, and seismologic (LaCroix, 1980, MGS 2005) and include events that:

- Occur in the early morning hours commonly from midnight to just before sunrise.
- Show no association with recorded seismic activity during the time of the report and are often reported for only a singular location.
- Take place during the colder winter months from December to February.
- Occur after a considerable rapid temperate drop such as when a Polar Vortex occurs.
- Are found where permeable soils are susceptible to frost action such as sandy and gravely soils (meaning lots of pore space filled with groundwater that can freeze rapidly).

Cryoseisms have been reported in several mostly northern states including Alaska, Wisconsin, Michigan, Indiana, Ohio, New York, Vermont, Maine, Massachusetts, Connecticut and now, possibly, North Dakota. These types of events are likely under reported, possibly just shrugged off as local anthropogenic activities, or mistakenly cataloged as apparent low-magnitude earthquake events in other parts of the country.

Of the few reports that we have received so far, other explanations are also possible. Please feel free to contact us if you happen to experience any perceived ground shaking, and we will follow up on your report in a timely manner. You can contact me directly at 701-328-8037 or via email at: fjanderson@nd.gov

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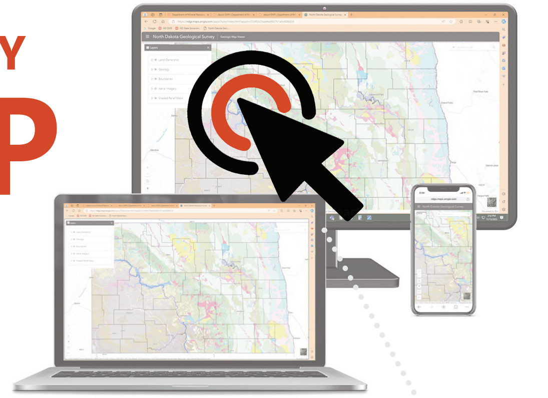
TABLE 1. Summary of potential cryoseismic events reported in North Dakota.

Date	Time	Location	Reported Effects	Outside Air Temperature[1]	NDGS Comments	Likely Cause
1/24/2018	01:30 AM	Southeastern Minot, North Dakota	Apartment resident felt interior walls of room shake abrubtly during the early morning hours. Reported as an abrubt jolt with no sustained duration of shaking.	9°F, -12.8°C	No seismic activity recorded on monitoring stations during last 24 hours. No local events reported by the USGS through the NEIC. Recent M 7.9 Alaska earthquake has been in the news the last few days. No additional reports received for the area.	Residential activity in the building occurring in the early morning hours.
12/4/2018	12:33 AM	Northeastern Tioga, North Dakota	Trailerhome resident reports trailer shaking during the middle of the night. Trailer wobbling like when clothes dryer is spinning.	10°F, -12.2°C	No seismic activity recorded on monitoring stations during last 24 hours. No local events reported by the USGS through the NEIC. Recent M 7.1 Alaska earthquake has been in the news the last few days. 4 SWD wells within 3 miles of Tioga. No additional reports received. for the area.	Possible cryoseism or high-wind gusts.
2/8/2012	Early Morning Hours	Ft Yates, North Dakota	Heard a large "boom" sound coming from the river.	2°F, -16.7°C	No seismic activity recorded on monitoring stations during last 24 hours. No local events reported by the USGS through the NEIC. No additional reports received for the area.	Possible Cryoseism - Ice activity on Lake Oahe.
3/27/2007	Early Morning Hours	Central Mandan, North Dakota	Felt house shaking during the early morning hours.	31°F, -0.6°C	No seismic activity recorded on monitoring stations during last 24 hours. No local events reported by the USGS through the NEIC. No additional reports received for the area.	Possibly Mandan rail yard activity.

[1] Meteorlogical Data from the North Dakota Agricultural Weather Network (NDAWN).

NORTH DAKOTA GEOLOGICAL SURVEY

GEOLOGIC MAP VIEWER:



Touring the State's New Online Resource

https://www.dmr.nd.gov/dmr/ndgs/geologic-map-viewer

BY BENJAMIN YORK

We are excited to announce the unveiling of the North Dakota Geological Survey's (NDGS) *Geologic Map Viewer*! This new *Geologic Map Viewer* (fig. 1), referred to as the *Viewer*, provides a wealth of information about the geology of the state, making it an essential resource for anyone seeking to view North Dakota geology and topography in an easy-to-use application. The *Viewer* is a compilation of datasets published by the NDGS and other agencies which, when layered over each other, present a comprehensive and insightful display of data. It includes detailed information about the state's geology, boundaries, yearly aerial imagery, and monumental datasets such as 1-meter LiDAR (Light Detection and Ranging) derived hill shade of the entire state.

One of the key features of the *Viewer* is its accessibility. Anyone with an internet connection can access it on a variety of devices, such as phones and computers, making it an invaluable resource for researchers, students, and anyone else who wants to learn more about North Dakota's geology.

The *Viewer* is also designed to be user-friendly, with a simple, intuitive interface that makes it easy to find the information you need. Without online applications such as the *Viewer*, someone would have to bring all the separate layers into Geographic Information Systems (GIS) software and adjust the colors and transparency to make the data usable.

The *Viewer* is always evolving and being updated with the latest datasets that the NDGS feels are beneficial and compatible with the viewer. Some datasets are exclusively hosted by the NDGS, while the remaining reference datasets are found on the ND GIS Hub (*https://www.gis.nd.gov*). Currently, the sub-layers in the "Layers" section (fig. 2) include, in order, Land Ownership, Geology, Boundaries, Aerial Imagery, and Shaded Relief Map. To view the attribute table filled with information about each polygon, click the item and a pop-up will display (fig. 3).

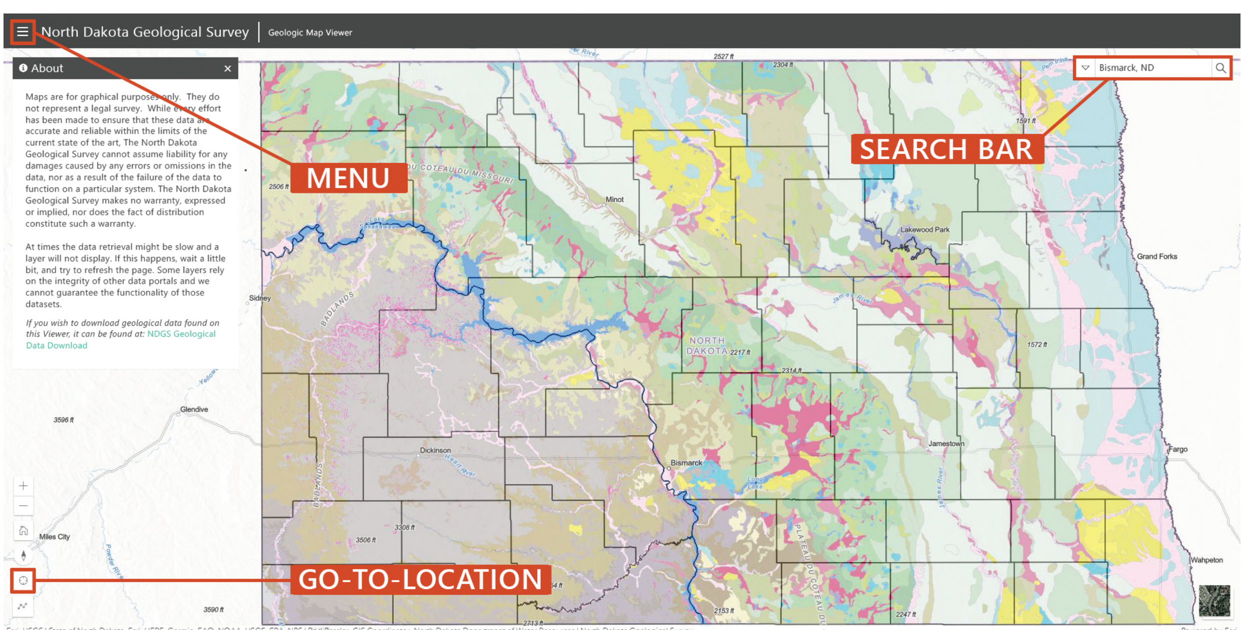


FIGURE 1. Here is the *Geologic Map Viewer* after the website is launched. The 1980 surface geology map by Clayton is the first thing you'll see along with the "About" section in the upper left. Some useful tools are the "Search bar" in the top right, and the "Show location" in the bottom left. You can access other basemaps and layers by clicking the three horizontal bars in the top left, which is the "Menu".

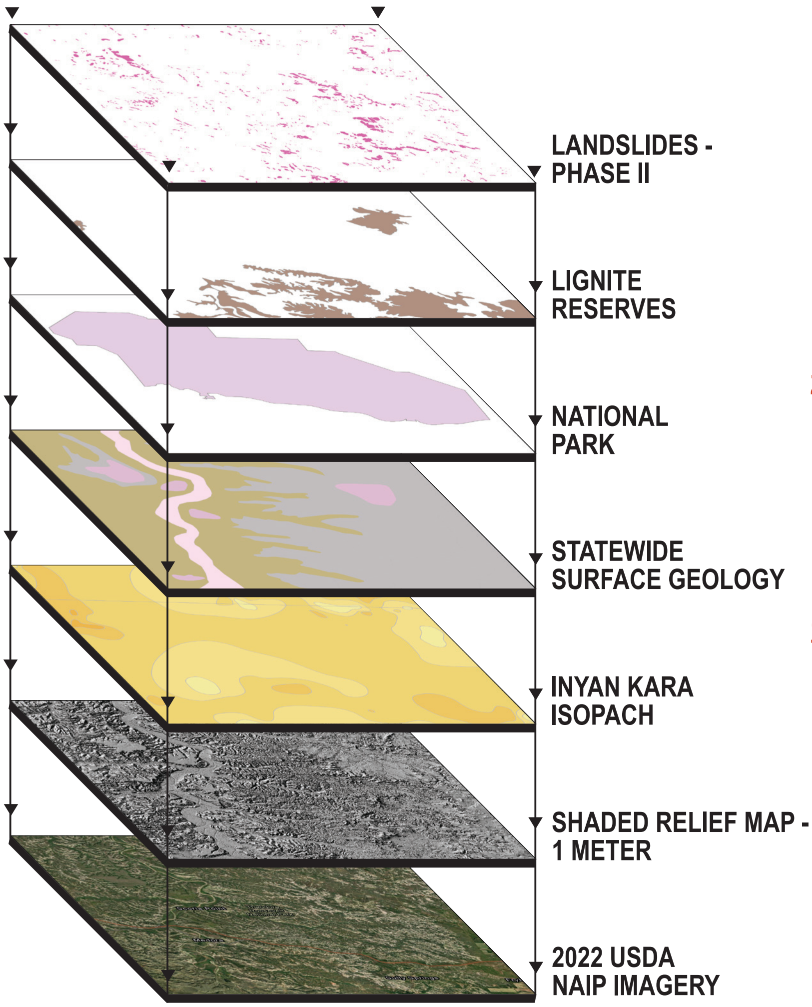


FIGURE 2.
This figure demonstrates the effectiveness of stacking layers within the *Viewer*. Any of these layers can be toggled on or off to create a unique composition for understanding that area of the map. This area depicted is in and around the South Unit of the Theodore Roosevelt National Park.

LAND OWNERSHIP

The first sub-layer that you will have the option to toggle on and off includes Federal and State Government owned lands. For Federal, this includes layers such as Bureau of Land Management, Bureau of Reclamation, and national parks and grasslands. For State, some useful layers to switch on and off would be trust lands, and state parks and forests.

GEOLOGY

Many of the geology datasets have been digitized from paper maps. All layers exclusively hosted by the NDGS rather than the ND GIS Hub can be found here in the Geology sub-layer. At present, with the intention to add more, the geology sub-layer contains the following datasets:

1) Statewide Landslides

"Landslide areas in North Dakota are depicted on this map as mapped from historical aerial photographs, recent digital aerial imagery, and LiDAR digital elevation models, over seven years from 2016 to early 2023. These landslide areas were mapped at variable scales generally at 1:12,000 or less and presented at 1:24,000 scale in 1,476 individual quadrangles that cover the state. A total of 66,000 landslide areas were identified based dominantly on their surficial geomorphological expression and represent landslide areas identified up to the last date of LiDAR data collection available." – Excerpt from NDGS Areas of Landslides in North Dakota, Geologic Investigations No. 269 (Anderson et al., 2023).

2) Statewide Surface Geology and Landforms

This map shows the distribution of surface geologic units in the state of North Dakota. The coverage contains only area features. Linear features, such as beach ridges, eskers, and ice margins, are contained in the Landforms layer. The original data is derived from the 1:500,000 Geologic Map of North Dakota (Clayton et al., 1980).

3) Statewide Bedrock Geology

Digitized geologic bedrock map of North Dakota from NDGS Miscellaneous Map No. 25 (Bluemle, 1983). The primary source of information used to compile the original map was the test-hole data obtained during drilling by the North Dakota Department of Water Resources for their groundwater studies. The NDGS and U.S. Geological Survey were also involved in these groundwater studies. The map is only as accurate as the density and reliability of the control points. The bedrock geology map is precise in the southwestern part of the state where there are bedrock surface exposures, but less precise in areas of thick glacial overburden where only a few test holes reached bedrock.

4) Coal Reserves

This layer of strippable lignite deposits in North Dakota is from NDGS Miscellaneous Map No. 34 (Murphy, 2001). The reserves were calculated using geophysical logs from over 18,000 holes, including test holes on file with the NDGS and USGS. Western and central North Dakota are underlain by approximately 32,000 square miles of lignite deposits, with some deposits near the surface and others extending as deep as 1,800 feet or more. Using the calculations described in MM 34, it is determined that North Dakota contains 25.1 billion tons of strippable lignite reserves.

5) Earthquake Locations

This layer is a point file of all earthquakes that have an epicenter in North Dakota. Each point has location, magnitude, intensity, and estimated depth information associated with it. The information was collected from multiple sources and published in the NDGS Geologic Investigations No. 187 (Anderson, 2015).

6) Inyan Kara Formation

This layer is an isopach map, displaying thickness contours, of interpreted injectable sandstone bodies of the Inyan Kara Formation of the Dakota Group. The Inyan Kara Formation consists of marginal marine and non-marine sandstone and shale. The purpose of this layer is to identify favorable areas where the potential for encountering sandstone bodies for injecting produced water is greater. This layer was prepared using wireline logs (gamma ray and resistivity) from thousands of wells and is a compilation of fifteen 100K maps.

BOUNDARIES

Like the land ownership sub-layer, the boundaries datasets are useful for geographic references and visualizing how geology aligns with political and civil borders. Datasets such as county boundaries, reservations, 1:24,000 quadrangles, and PLSS townships and sections have relevance to geology datasets provided on the *Viewer*.

AERIAL IMAGERY

In addition to the default Imagery base map, the *Viewer* also has various aerial imagery that can be used for reference. The primary dataset is the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP). Currently, the *Viewer* displays NAIP imagery from 2003-2022. NAIP imagery is collected during the active agriculture season with the primary recipient being the USDA Farm Service Agency. The imagery is useful for repeat analysis since it is captured roughly the same time every year.

The remaining imagery is various historical datasets from several agencies. The oldest statewide imagery is the USDA 1957-1962 aerial dataset. This can be especially useful to see the terrain before all of the anthropogenic changes such as urban development or road installation had taken place. It can also be useful for visualizing how long certain landslides have been active. Using the USDA 1957-1962, USGS 1995-1998, and the most recent USDA 2022 imagery you can see how a location has changed in roughly 30-year increments.

SHADED RELIEF MAPS

The *Viewer* displays 1-meter and 10-meter resolution statewide hill shade models, or shaded relief map, which simulates the sun's effects and creates shadows and shading to create a clearer picture of what the topography looks like. To learn more about shaded relief/hill shade maps, check out this Esri blog (Nagi, 2014).

The 1-meter shaded relief map is derived from LiDAR. LiDAR is typically collected from aircraft and is usually delivered as a point cloud dataset, and then is converted into a digital elevation model (DEM) which is easier for scientists to work with. For more information on how the NDGS uses LiDAR and its derivatives, please check out these newsletter articles about LiDAR (Maike, 2016, 2021). The *Viewer* connects to an elevation data portal hosted by the North Dakota Department of Water Resources (NDDWR). Through the NDDWR LiDAR portal (*https://lidar.dwr.nd.gov*), a user could download individual collection tiles, but the *Viewer* instead connects to an already rendered statewide shaded relief map. This allows users of the *Viewer* to overlay other useful datasets right over the modeled terrain.

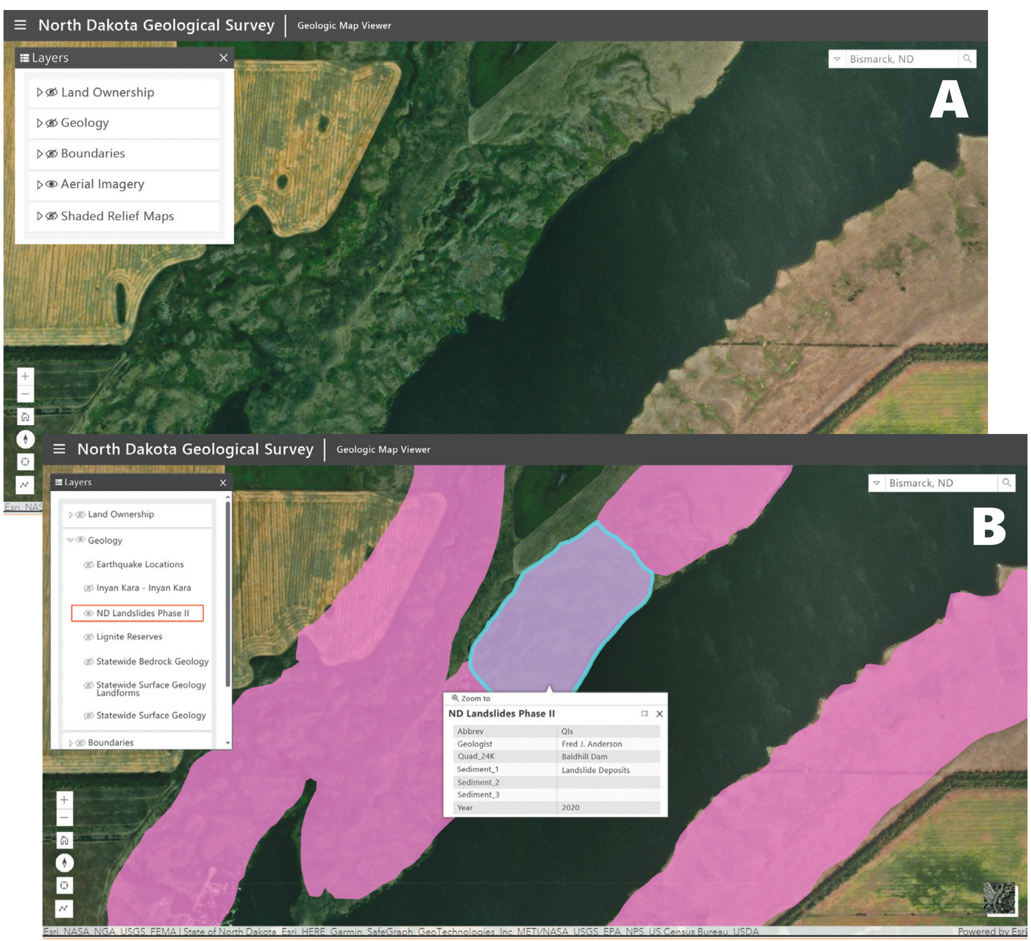


FIGURE 3. The "Layers" located in the menu (three horizontal bars in the top left), contains **(a)** all the information that the *Viewer* has to offer. Many of these layers, such as the Land Ownership and Boundaries, are from others state of federal agencies, but all of the layers in the Geology section are produced by the NDGS. Within the *Viewer* the user can click on any feature to show the attribute table. The feature highlighted in the figure **(b)**, a landslide north of Valley City, displays the attribute table containing information such as the year the feature was mapped, and who mapped it.

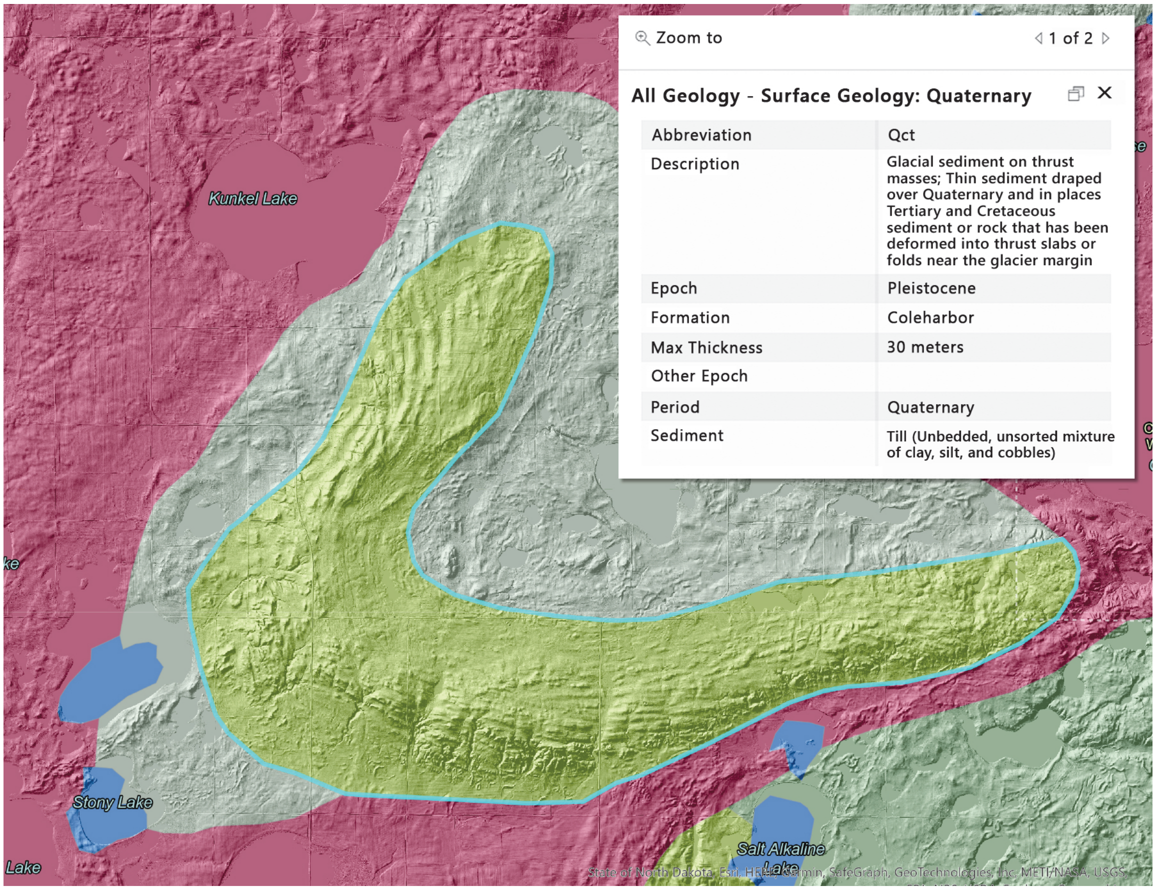


FIGURE 4. The *Viewer* can also display multiple layers at the same time to create an even more useful dataset. One example of this layer combination would be displaying the Statewide Surface Geology over the 1-meter shaded relief map. The feature highlighted is a glacial thrust mass near Horsehead Lake in Kidder County. Some layers have detailed descriptions, such as this feature within the Surface Geology, seen in the attribute table.

The other shaded relief map on the *Viewer* is a 10-meter shaded relief map derived from the National Elevation Dataset (NED) originating from the USGS. The NED dataset is a compilation of LiDAR collects, contour maps, elevation collections, Shuttle Radar Topography Mission data, and other sources. The NED dataset covers the entire United States, but for the *Viewer*, just North Dakota is used for the statewide 10-meter shaded relief map.

CONCLUSION

In addition to all the layers that the *Viewer* has to offer, there are some additional features and tools the user has available to them. In the top right (fig. 1), there is a search bar where you can select different datasets to search locations. Under "Esri World Geocoder," you could search for town names or latitude/longitude, and you could even search for Township/Range/Section by selecting "PLSS Sections" in the drop-down. There is also a button in the bottom left, that looks like a target and crosshair, that will show your location within the *Viewer*; this is especially useful when using our application on a mobile device. These are just a few of the tools and features that the *Viewer* has to offer.

Having all of these layers present in one location, with all the colors and transparency already adjusted for ideal display, the *Viewer* alleviates the need for complex and expensive GIS software for those who just want to use maps for reference. Many NDGS datasets are published online as PDF or downloadable shapefile links, but having a one-stop-shop for geology and geography datasets saves time by removing the need to download data and manipulate the layers to make it useful.

A lot of work has gone into making the datasets that are displayed in the *Viewer*. The NDGS hopes that this new tool can serve the public well and will constantly evolve to meet the needs of both the public and industry. You can contact Benjamin York at ***bcyork@nd.gov*** with any comments or suggestions.

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REDEVELOPMENT OF MADISON FIELDS IN BURKE COUNTY DEMONSTRATES

Fracture Stimulation IS EFFECTIVE

BY EDWARD (TED) STARNS & TIMOTHY O. NESHEIM

Development of oil and gas in the Rival and Midale subintervals (Madison Group) in Burke County has seen nearly continuous drilling and production activity since shortly after the discovery of oil and gas in North Dakota and can serve as a case study for future redevelopment in other Madison fields (fig. 1). Over the long and diverse history of oil and gas development in Burke County, activity progressed from conventional vertical development to localized water flooding, to exploring and developing downhole potential in the Bluell subinterval in the early 1980s, ultimately evolving into an open hole horizontal play in the late 1990s. In 2012, the implementation of unconventional-style hydraulic fracture stimulation rounded out this play as a microcosm of the last 70 years of technological advances in the oil and gas industry. The success of the recent development implementing fracture stimulation bodes well for the remaining resource potential of the immediate area and other Madison fields in western and north-central North Dakota.

In 1955, four years after the discovery of oil in North Dakota, the Gunnar Opseth #1 well (NDIC 945) was producing ~800 barrels of oil per month from the Midale and upper Rival carbonate reservoirs in what would become the Coteau Field in southeastern Burke County. In the following years, 36 fields were discovered, and four distinct development strategies were applied to these conventional carbonate reservoirs (fig. 2).

The first decade of development in northern Burke County saw a flurry of activity (fig. 2), with nearly half of the total number of vertical wells drilled and completed in the first stage of development (484 producers - 194 dry holes). By 1960, there were 15 named fields in the region and unitization efforts were undertaken in the early to late 1960s (Anderson et al., 1960; Lindsay, 1985). The years that followed saw drilling activity and production decline in Burke County, except for a period of increased drilling in the early 1980s, which saw an increase in production primarily due to the development of the Bluell subinterval in the Flaxton Field (Voldseth, 1986), and some other peripheral Rival – Midale development (fig. 3).

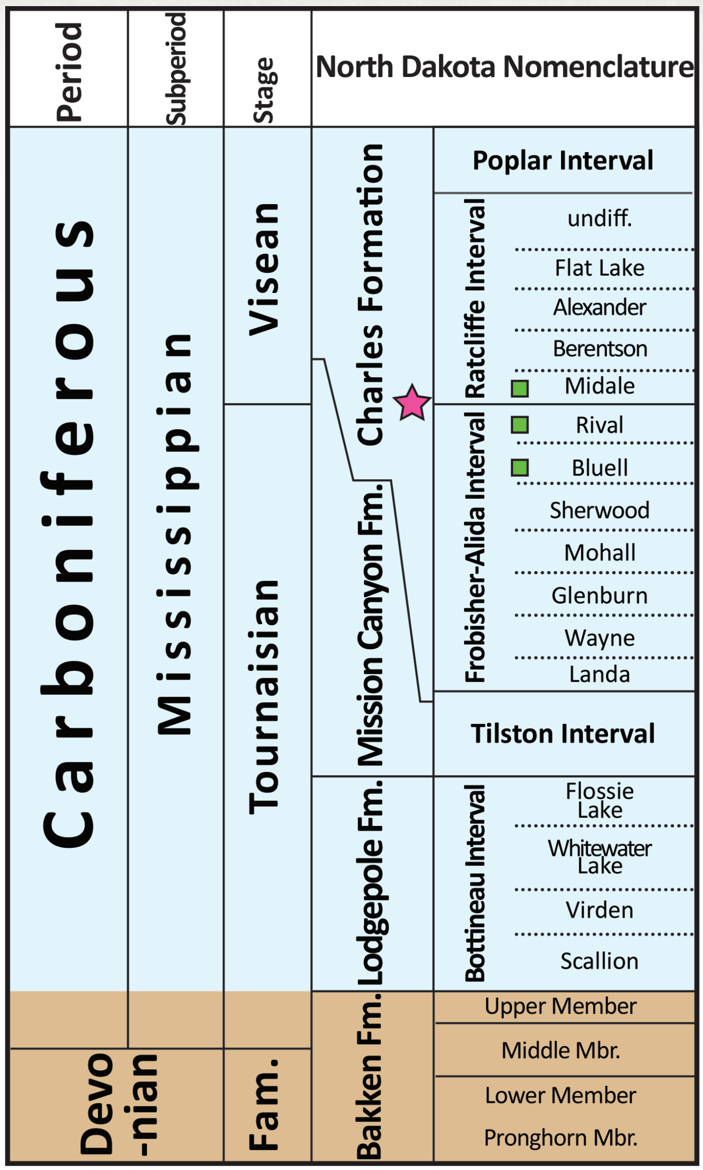

FIGURE 1.
Simplified stratigraphic column of the lower Mississippian and upper Devonian section in the Williston Basin, North Dakota, highlighting the location of the Midale, Rival, and Bluell subintervals of the Madison Group. The pink star highlights the Midale and Rival subintervals, the primary producing intervals discussed here. Modified from Nesheim and Onwumelu, 2022.

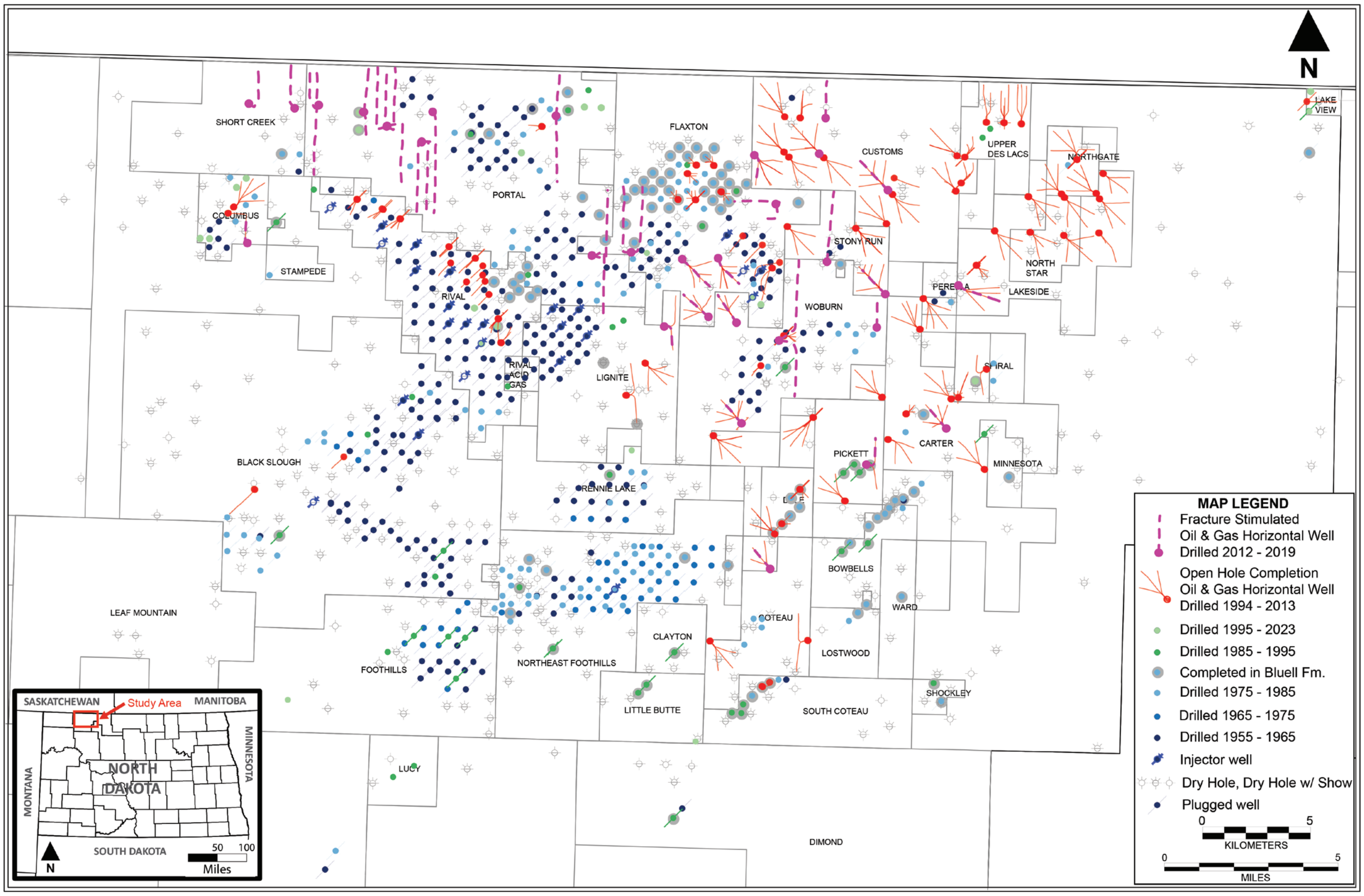

FIGURE 2.

Drilling activity in northern Burke County by decade. Most vertical and horizontal wells target the Rival and/or Midale subintervals; light gray circles highlight wells completed in the Bluell subinterval.

In 1994, the Taylor Layne 25H-1 (NDIC #13700) was drilled in the Rival Field as the first open-hole lateral completion. A total of 95 wells with 258 laterals, commonly multi-lateral projects, would eventually employ this development technique. This development effort had the upper Rival as its primary target, with the Midale a secondary target that would be drilled with a dedicated lateral in some projects. These wells helped to stem the production decline of the area, but had variable results.

The introduction of fracture stimulation to the area saw a staged approach where some existing open-hole laterals were recompleted as single laterals and fracture stimulated, beginning with the Ormiston Unit 1. Originally drilled as a dual lateral open hole completion in 2006, it was recompleted and fracture stimulated in 2012, resulting in a promising bump in production (see NDIC #16072 production data for details). Within two years, fracture stimulation was the dominant development strategy in the region, and 43 single lateral wells (including recompletions) were fracture stimulated through 2020. Recompletions and dedicated laterals for fracture stimulation were implemented in tandem during this period, with a campaign of recompletions in 2017 which yielded variable but promising results. Dedicated laterals with fracture stimulations averaged 15 stages, 1.5 million pounds of proppant, ~30,000 barrels of fluid, and ~7,000′ in lateral length – on the smaller end of other unconventional development strategies in the Williston Basin.

As a whole, fracture stimulation has been the most effective development technique applied to the region from the stance of consistency and expediency of production (i.e., rate acceleration). Cumulative production and production rates increased with the help of fracture stimulation of undeveloped resources adjacent to existing production, notably in the Portal Field. Note the total oil production from 2015 – 2019 in Figure 3, and cumulative production values from 2012 – 2019 in Table 1. Fracture-stimulated wells made a significant contribution in production of oil and gas with fewer wells over a shorter period. Drilling activity came to a halt during the Covid-19 pandemic in 2020 with a resultant decrease in production (fig. 3).

As of December 2022, Burke County Madison fields have produced 60.4 million barrels of oil, 146.3 million barrels of water, and 107.8 billion cubic feet of gas – a long-lived development of an established resource that has provided returns for close to three-quarters of a century (Table 1). The development of the Rival - Midale Formations in northern Burke County can serve as a case study for the scale and scope of other Madison Group redevelopment. The success of fracture stimulation treatments in Burke County oil fields suggests it is an effective method to increase oil recovery in legacy fields and their surroundings, with significant room for future development in the immediate area and beyond.

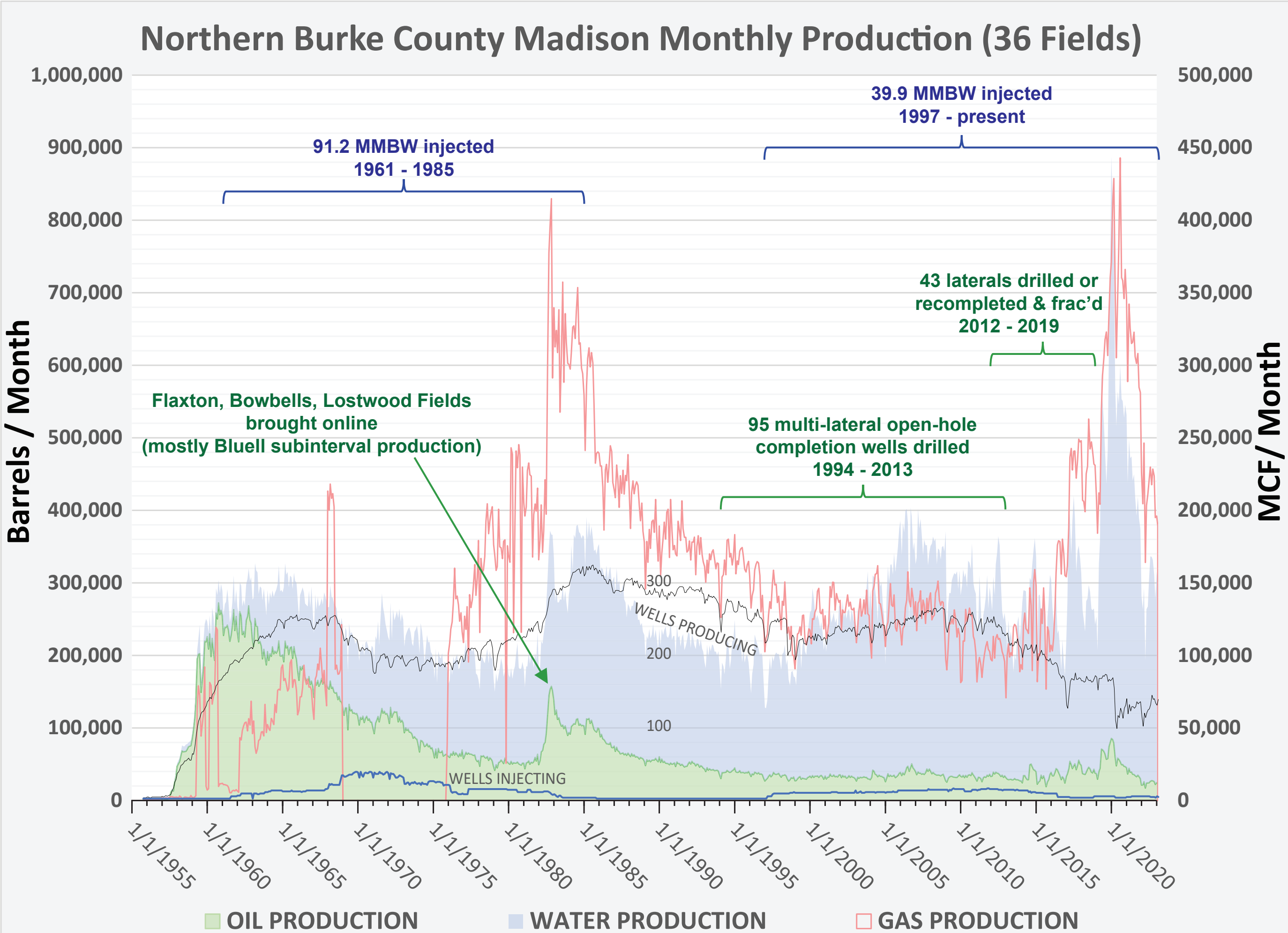

FIGURE 3.
Historical production of oil, water, and gas for 36 Madison fields in Burke County, highlighting the impact of the four different development styles over time.

This retrospective speaks to a promising future for the continued development of the Madison Group in North Dakota – the second-largest producing formation by volume in the history of North Dakota's journey of oil and gas development (Nesheim and Onwumelu, 2022). By developing around existing fields in Burke County, operators have demonstrated that areas where the Madison reservoirs had been uneconomic as conventional developments due to low permeability can have development potential with new technologies (i.e., fracture stimulation). Additional details on the fracture-stimulated wells, an analysis of the geological setting and sedimentological drivers of reservoir performance, and maps of production can be found in North Dakota Geological Survey publication GI 272.

TABLE 1.
Cumulative production through December 2022 for the Madison Group from the 36 oil fields of northern Burke County.

Well Type	Dates	Count	Oil Production MMBO	Water Production / Injection MMBW	Gas Production BCF
Vertical Producers	1955 - 2011	607 (435 dry)	51.4	79.5	73.7
Vertical Injectors	1961 - 1985 1997 - present	28	N/A	131.2	N/A
Open-hole Multi-lateral Horizontal Producers	1994 - 2013	95 (258 laterals)	5.9	40.4	15.4
Fracture Stimulated Single-lateral Horizontal Producers	2012 - 2019	43 (15 recompletions)	3.1	26.4	18.7
Totals		**1371**	**60.4**	**146.3**	**107.8**

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NEW PUBLICATIONS

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

GEOLOGIC INVESTIGATIONS

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Anderson, F.J. and Murphy, E.C., 2023, Areas of Landslides Taylor Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Tylr - I3.

Anderson, F.J. and Murphy, E.C., 2023, Areas of Landslides Wolf Coulee Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. WlfC - I3.

Maike, C.A., 2023, Areas of Landslides York Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. York - I3.

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Maike, C.A., 2023, Areas of Landslides Wolford Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Wlfd - I3.

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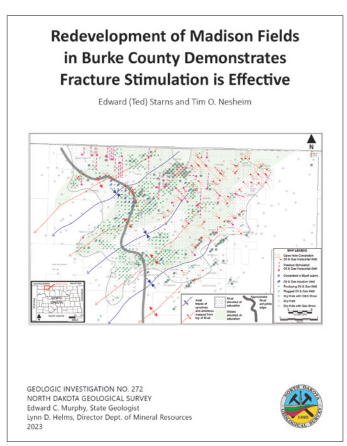

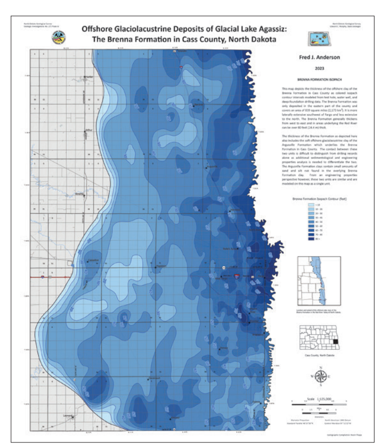

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Maike, C.A., 2023, Areas of Landslides Juanita Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Jnta - I3.
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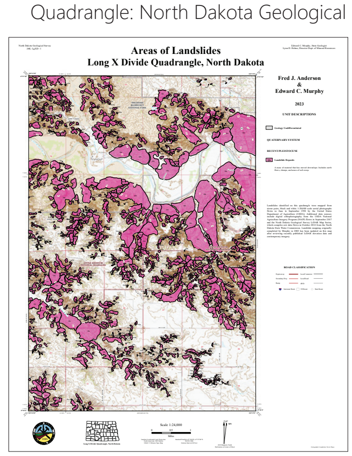

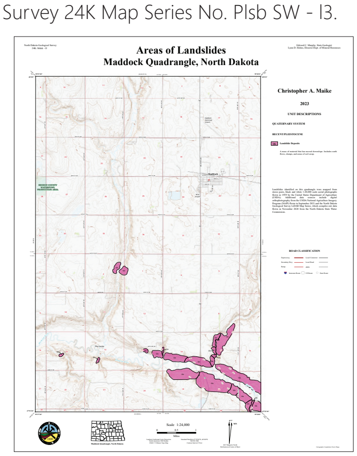

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Maike, C.A., and Moxness, L.D., 2023, Areas of Landslides Blabon Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Blbn - l3.

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Maike, C.A., and Moxness, L.D., 2023, Areas of Landslides Luverne NW Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Lvrn NW - l3.

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Moxness, L.D., 2023, Areas of Landslides Silverleaf Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Svrl - l3.

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Moxness, L.D., 2023, Areas of Landslides Medberry Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Mdbr - l3.

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Moxness, L.D., 2023, Areas of Landslides Berlin Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Brln - l3.

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Moxness, L.D. and Biek, R. F., 2023, Areas of Landslides Davis Buttes Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. DvsB - l3.

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York, B.C. and Anderson, F.J., 2023, Areas of Landslides Northwood Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Nrwd - l3.

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York, B.C. and Anderson, F.J., 2023, Areas of Landslides Edinburg Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Ednb - l3.

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York, B.C. and Maike, C.A., 2023, Areas of Landslides Lake Pickard Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. LkPk - l3.

York, B.C. and Maike, C.A., 2023, Areas of Landslides Kempton Quadrangle, ND Quadrangle: North Dakota Geological Survey 24K Map Series No. Kmpt - l3.

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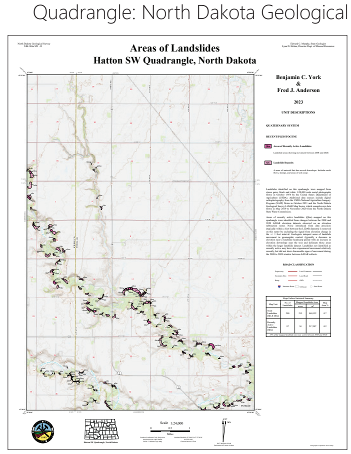

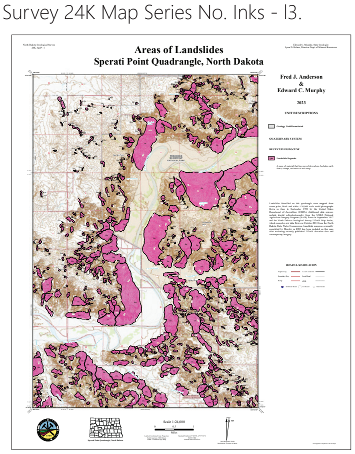

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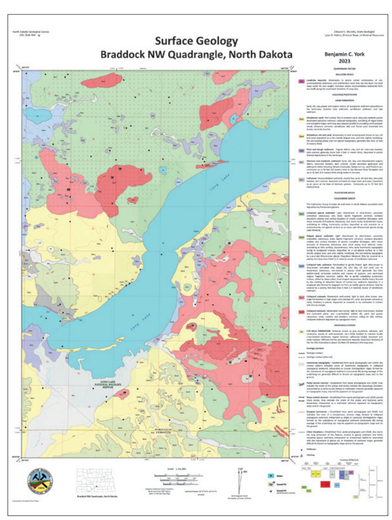

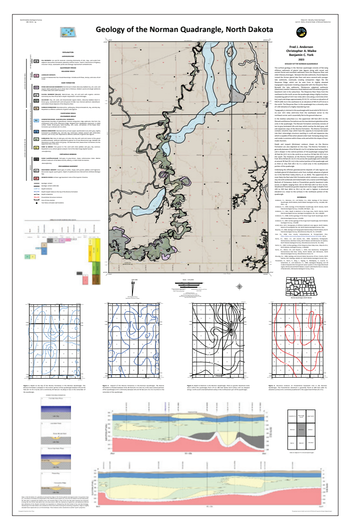

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