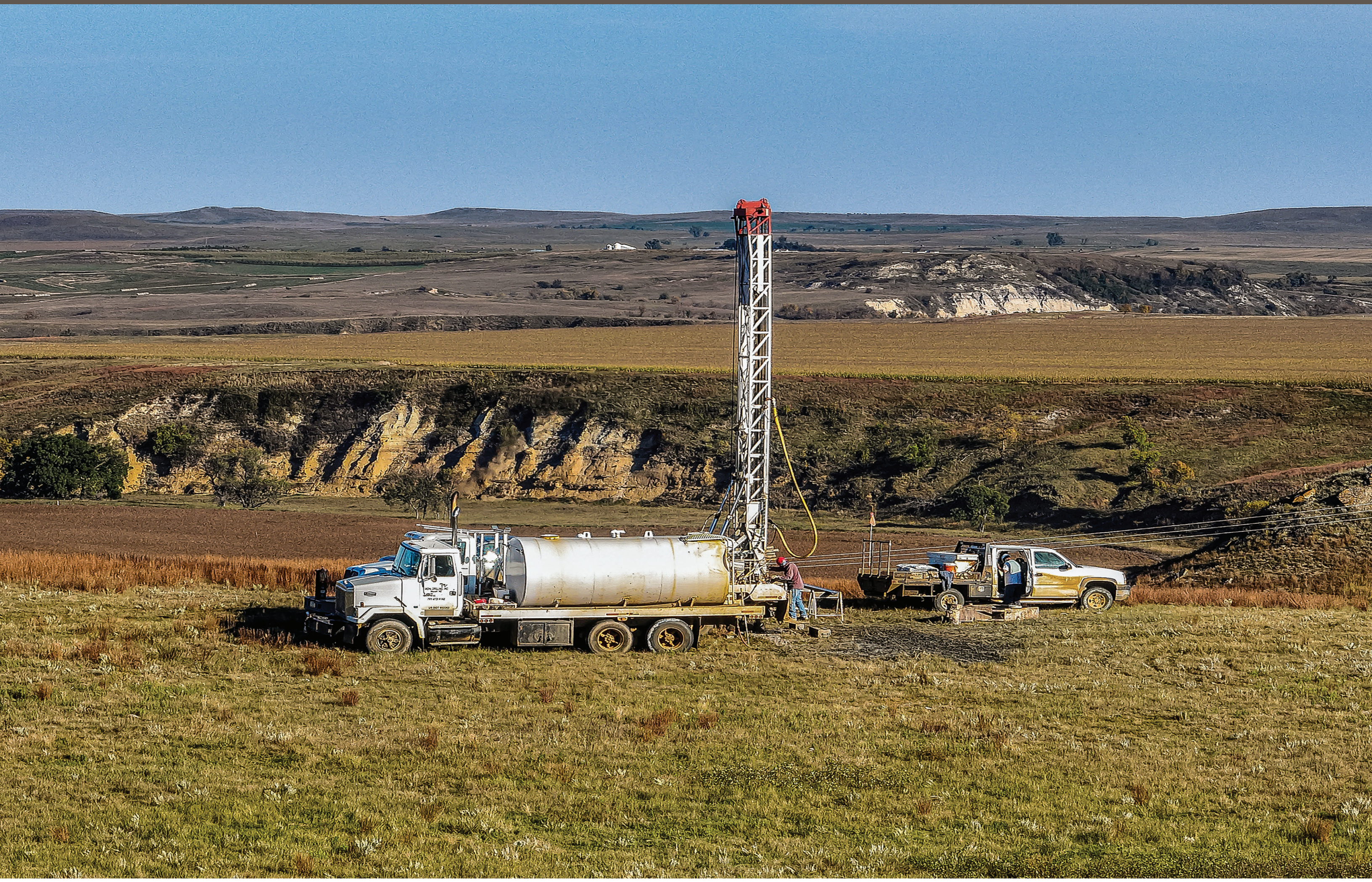

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Be Legendary.™

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FEATURES

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ON THE COVER:
John Mohl and crew of Mohl Drilling, Inc. recovering core along the Cannonball River in Grant County during the North Dakota Geological Survey's critical mineral drilling program in September 2025.

THE EVOLUTION OF THE DEPARTMENT OF INTERIOR'S CRITICAL MINERAL LIST

BY NED W. KRUGER

No less than every three years, the U.S. Secretary of the Interior is required by law to review and revise the U.S. List of Critical Minerals and also the methodology used in its evaluation of mineral commodity supply risk. Spearheaded by the U.S. Geological Survey, which sets the parameters for the risk evaluation and posts a draft list in the Federal Register for 30 days of public comment, the most recent final list was released on November 6th, 2025, identifying 60 qualifying minerals. The list informs and influences investment in mining and processing of minerals and guides U.S. tax incentive and permit streamlining initiatives.

> *"A 'critical mineral' is a mineral identified by the Secretary of the Interior… to be (i) a non-fuel mineral or mineral material essential to the economic and national security of the United States, (ii) the supply chain of which is vulnerable to disruption, and (iii) that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security."*
> – from Executive Order 13817

HISTORY OF THE LIST

National attention to finding domestic sources of critical minerals was heightened with the issuance of Executive Order 13817 - *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* by President Donald Trump on December 20, 2017. In a fortunate coincidence of timing, the day was also that on which the NDGS published RI-117 (Kruger et al., 2017), the first report of our investigation into the potential of North Dakota's lignite as an alternative source of rare earth elements (REE), an important subset of critical minerals. This investigation began in the fall of 2015, giving our state a two-year head start on the federal push to produce new critical mineral data. RI-117 reported some of the highest REE concentrations in coal known in the country.

The first critical mineral draft was put out for public comment in February of 2018, containing 35 mineral commodities deemed critical by the definition given in the executive order (see inset). Two listed commodities were actually mineral groups, the Platinum Group Metals and the Rare Earth Elements Group, which were broken out as individual mineral commodities on subsequent lists (Table 1). After the public comment period, the USGS made no changes and the 35 minerals were accepted for the 2018 List of Critical Minerals (DOI, 2018). Although uranium is a mineral fuel, it was included on the 2018 list because this initial list was mandated by an executive order rather than law, which gave the USGS flexibility to consider other policy goals in its implementation.

The List of Critical Minerals is largely based upon market conditions and policy priorities reflective of the point in time at which it is written. The Energy Act of 2020 (Energy Act) further directed the Secretary of the Interior to review and revise both the List of Critical Minerals and the methodology used to compile the list at least every three years. The methodology was updated to perform quantitative supply risk assessments when data is available and to consider single points of supply failure and other qualitative assessments when data is insufficient. The draft list, published in November 2021, added nickel and zinc and removed five minerals. Helium was removed because its supply chain risk did not meet the new criteria, and there was also no risk of a single point of supply failure. It was recognized that the U.S. is largely import-reliant on potash, rhenium, and strontium, however the likelihood of disruptions was deemed low for these three minerals, which were also removed from the list. Finally, with the Energy Act codifying the definition of critical minerals as being "non-fuel" in statute, uranium was removed from the list. This was done as a matter of definition rather than by a downgrade of strategic value or supply risk. The USGS received over 2,000 responses during an extended comment period but ultimately moved forward with 50 minerals from its draft list to the final 2022 List of Critical Minerals without additional changes (USGS, 2022).

The draft list prepared by the USGS in 2025 used an updated methodology taking into consideration economic-effect assessments to estimate potential impacts of supply disruptions, and recommended the addition of copper, lead, potash, rhenium, silicon, and silver, and the removal of arsenic and tellurium based on updated risk and economic impact modeling. Following the draft release, boron was added to the list based on information gathered during the public comment process. Secretary Burgum also used the broad authority designated to him by the Energy Act to list minerals recommended for inclusion by the Departments of Energy (metallurgical coal & uranium), War (arsenic &

tellurium), and Agriculture (phosphate) (USGS, 2025).

The Energy Act also requires the Department of Energy to compile a list of energy-critical *materials*. The "critical material" definition emphasizes the material's essential function in energy technologies which produce, transmit, store, and conserve energy. It lists the names of those minerals that fit its definition and also recognizes the DOI's List of Critical Minerals as an additional part of the "Materials" list (see Table 1). The "material" and "mineral" lists have some overlap and can easily be confused with one another.

Of the top ten mineral commodities ranked by estimated probability-weighted impact of supply disruptions on the U.S. economy during the 2025 process, five were rare earth elements (samarium, lutetium, terbium, dysprosium, and gadolinium) (DOI, 2025). The NDGS has been actively investigating rare earth elements and other critical minerals for the past 10 years, most recently by carrying out drilling programs targeting two stratigraphic zones our reports have identified as sources of rare earth elements enrichment. Eight publications have been generated from these investigations and are available for download at the NDGS website.

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TABLE 1.
The table shows the progression of minerals appearing on the Department of Interior's List of Critical Minerals finalized for the years 2018, 2022, and 2025. For comparison, it also presents the Department of Energy's Critical Materials for Energy (DOE, 2023).

Critical Minerals & Energy Materials			
Critical Minerals			Energy Critical
2018	2022	2025	Materials - 2023
Aluminum (bauxite)	Aluminum	Aluminum	Aluminum
Anitimony	Anitimony	Anitimony	
Arsenic	Arsenic	Arsenic	
Barite	Barite	Barite	
Beryllium	Beryllium	Beryllium	
Bismuth	Bismuth	Bismuth	
		Boron	
Cesium	Cesium	Cesium	
Chromium	Chromium	Chromium	
Cobalt	Cobalt	Cobalt	Cobalt
		Copper	Copper
Fluospar	Fluospar	Fluospar	
Gallium	Gallium	Gallium	Gallium
Germanium	Germanium	Germanium	
Graphite (natural)	Graphite (natural)	Graphite (natural)	Graphite (natural)
Hafnium	Hafnium	Hafnium	
Helium	~~Helium~~		
Indium	Indium	Indium	Indium
		Lead	
Lithium	Lithium	Lithium	Lithium
Magnesium	Magnesium	Magnesium	Magnesium
Manganese	Manganese	Manganese	
		Metallurical coal	Metallurical coal
	Nickel	Nickel	Nickel
Niobium	Niobium	Niobium	
		Phosphate	
Platinum Group Metals	Iridium	Iridium	
	Palladium	Palladium	
	Platinum	Platinum	Platinum
	Rhodium	Rhodium	
	Ruthenium	Ruthenium	
Potash	~~Potash~~	Potash	
Rare Earth Elements Group	Cerium	Cerium	
	Dysprosium	Dysprosium	Dysprosium
	Erbium	Erbium	
	Europium	Europium	
	Gadolinium	Gadolinium	
	Holmium	Holmium	
	Lanthanum	Lanthanum	
	Lutetium	Lutetium	
	Neodymium	Neodymium	Neodymium
	Praseodymium	Praseodymium	Praseodymium
	Samarium	Samarium	
	Terbium	Terbium	Terbium
	Thulium	Thulium	
	Ytterbium	Ytterbium	
	Yttrium	Yttrium	
Rhenium	~~Rhenium~~	Rhenium	
Rubidium	Rubidium	Rubidium	
Scandium	Scandium	Scandium	
		Silicon	Silicon
		Silver	
Strontium	~~Strontium~~		
Tantalum	Tantalum	Tantalum	
Tellurium	Tellurium	Tellurium	
Tin	Tin	Tin	
Titanium	Titanium	Titanium	
Tungsten	Tungsten	Tungsten	Also...
Uranium	~~Uranium~~	Uranium	Flourine
Vanadium	Vanadium	Vanadium	Electrical Steel
	Zinc	Zinc	Silicon carbide
Zirconium	Zirconium	Zirconium	

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

2026 PUBLIC FOSSIL DIGS

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

Opens January 31, 2026 at 10am Central @ www.ndpaleofriends.org

Travel back to when North Dakota was like an African safari, southwest of Dickinson. Prehistoric mammals like rhinoceros, saber-toothed cats, and a plethora of small rodents, along with birds, alligators, and fish can be found in the 32-million-year-old rocks of the Little Badlands region of North Dakota.

Edmontosaurus, ***T. rex***, and ***Triceratops*** *oh my!!* Discover these dinosaurs and more south of Bismarck-Mandan in the 67-million-year-old Hell Creek Formation. These rocks preserve North Dakota's delta environment and all the creatures that lived within.

"Call me Ishmael" and travel 80 million years into the past, unearthing fish and giant swimming reptiles called mosasaurs. This locality in northeastern North Dakota dives into the Pierre Formation and the shallow sea that divided North America in two.

We won't be visiting the dig site near Medora this year because we have a scheduling conflict with other work we will be doing in June. We hope to return there in 2027.

GENERAL DIG INFORMATION

- All fossils collected on these digs go to the North Dakota State Fossil Collection and are used for educational and research purposes.
- Participants must bring their own lunches at all dig locations.
- Shade tents and port-a-potties will be available on-site.
- The experienced 2-day site closing session(s) may finish early on the second day.
- Our digs have a minimum age of 15 years for a full day and 10 years for a family half-day. Sorry, there are no digs for children under 10 years old.
- NO PERSONAL VEHICLES! All participants will be transported by van from the meeting site to the dig site and back.

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

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

Find more information on early registration opportunities at:

www.ndpaleofriends.org

BECKY BARNES

NORTH DAKOTA GEOLOGICAL SURVEY SENIOR PALEONTOLOGIST, LAB LEAD

BY JEFF PERSON AND CLINT BOYD

Becky Barnes served as a fossil preparator and supervisor of the Johnsrud Paleontology Lab for the North Dakota Geological Survey for over 17 years. She was hired in 2008 during the early years of the public fossil dig program and played a large part in the development and success of the program in the years that followed. Her kindness, likability, and authenticity made her a reason why many people would return to the summer dig program each year. Becky earned her undergraduate degree in Biology from Concordia College in Moorhead, MN and a Master of Science degree from North Dakota State University in Fargo, ND. She studied the osteology of the duck-billed dinosaur *Edmontosaurus* for her master's thesis, making her a very valuable resource on our most popular public dig south of Bismarck-Mandan. She was able to identify many of the dinosaur bones when only small portions were visible, allowing us to make accurate decisions on how to proceed with removing the fossil. She is also a talented fossil preparator, lending a hand in the preparation of Dakota the "Dinomummy" within the first week of her starting at the NDGS (fig. 1). She spearheaded the NDGS paleontology lab volunteer program and all the volunteers working in the lab today began under Becky's supervision.

Her creativity and talents as an artist can be seen throughout many aspects of the NDGS paleontology program. Her artistic additions to the program started small, but almost immediately had a positive impact. Her first dig-shirt design was in 2009 (fig. 2) and while it didn't always appear on a T-shirt, Becky took over the annual logo from that point on. She liked to change the theme of the artwork design (Aboriginal, Japanese, Celtic, etc.) as well as which dig and animals were featured (Pembina Gorge, Medora, Dickinson,

FIGURE 1.
Becky in 2008 working on the tail of Dakota.

and Bismarck digs). She is the author of six NDGS publications including two coloring books, two children's books, and two more scientifically oriented books about paleontology. She wrote and edited a total of 57 issues of the Fossils In North Dakota (FIND) newsletter, a short report that focused on fossils from the NDGS State Fossil Collection and recent finds from our summer digs. Her scientific artwork has been featured in two peer-reviewed articles, one describing a new specimen of the small Mesozoic mammal *Glasbius* and a second describing a new species of carnivore from the Oligocene (~32 million years old) that is closely related to today's bears. She has illustrations in the gallery of the Heritage Center and State Museum explaining erosion and coal formation that are also used in other natural history museums and publications. She also painted the large mural behind the elasmosaur neck on exhibit at the State Museum (fig. 3).

Her outreach included scientific talks, tours, and various other outreach activities. One of the most popular was the Prehistoric Fishing show that included Nori the mosasaur, a puppet she designed and built. She also created a popular card game called "Will You Survive" that is played during the NDGS Earth Day classroom activities. During COVID she spearheaded a video series featuring paleontologists from across the country talking about various aspects of paleontology, aimed at providing an education resource for teachers and kids stuck at home during the pandemic.

FIGURE 3.
Becky painting the mural for the elasmosaur exhibit at the Heritage Center. This painting was scanned and enlarged to be placed on the wall in the gallery.

FIGURE 2.
An example of Becky's early dig shirt designs. This one of a small mammal from the Medora dig is from 2010.

The examples above are only a fraction of the contributions that Becky made during her tenure with the NDGS. Becky is truly a "Jane of all trades" who made her impact felt throughout everything the NDGS paleontology program did over nearly two decades. In July of 2025, Becky moved to the Minneapolis area with her family to explore new opportunities. Her first public fossil dig was at the Medora site in 2008, and it was fitting that she spent her last days with us working at that same dig site this past June, completing the full circuit of her time at the Survey (fig. 4). She is missed, but the effects of her time with the NDGS will be evident for years to come and her contributions will not be forgotten.

FIGURE 4.
Becky in the field in 2008 (left) and 2024 (right).

FROM ABOVE THE WRECKAGE
UAS RELIEF IN ENDERLIN

BY CHRISTOPHER MAIKE

The night of June 20th, 2025, is one that residents of Enderlin, North Dakota, will never forget, as three lives were tragically lost to two tornadoes. The first tornado began shortly after 11:00 p.m., south of Enderlin and moved north while passing east of Enderlin. The tornado was rated an EF-5, with peak wind gusts in excess of 210 mph, and was on the ground for approximately 12 miles. The second tornado was generated to the northeast of Enderlin approximately 20 minutes after the first tornado. The tornado was classified as an EF-2, and it moved to the southeast for about 8 miles, crossing Highway 46, and dissipating soon after (fig. 1). It had peak winds reaching approximately 110 mph.

Late in the evening on June 23rd, a message was sent out to all State of North Dakota UAS pilots from the Northern Plains UAS Test Site (NPUASTS) requesting assistance to support clean-up efforts in the Enderlin area. North Dakota Geological Survey (NDGS) geologists, Christopher Maike and Levi Moxness, responded to the inquiry. They arrived early at the office to prep drones and supplies and then hit the road for Enderlin. They arrived at the Enderlin Fire Hall at 8:30 a.m. to join the local FFA and 150+ volunteers ready to support clean-up efforts. There was a total of eight drone pilots on site, with support from the NDGS, NPUASTS, and various local fire departments.

UAS Pilots were distributed among various groups to cover the greater Enderlin area. They were paired with groups of 10-15 individuals, assigned hundreds of acres of farm fields that needed to be surveyed to look for metal debris and large branches from destroyed shelter belts. The use of drones would save valuable time from people walking rows of farm fields. The NDGS was utilizing a DJI Mavic 3 Pro, which can reach speeds up to 47 mph. UAS pilots were quickly able to locate debris and coordinate with clean-up crews at the locations (fig. 2).

Why is the cleanup of fields important? At the time of the tornadoes, many crops were still in their infancy. Due to low crop heights, debris could easily be located. It was more important to clear debris for harvest later in 2025. For instance, a soybean header on a combine sits very close to the ground, and any large branches or metal would harm the machinery. A simple branch could break the header, setting the farmer back thousands of dollars in repairs and losing valuable time at harvest. While a lot of headway was made with the cleanup on June 20th, there were still days, if not weeks, of cleanup ahead for residents (fig. 3).

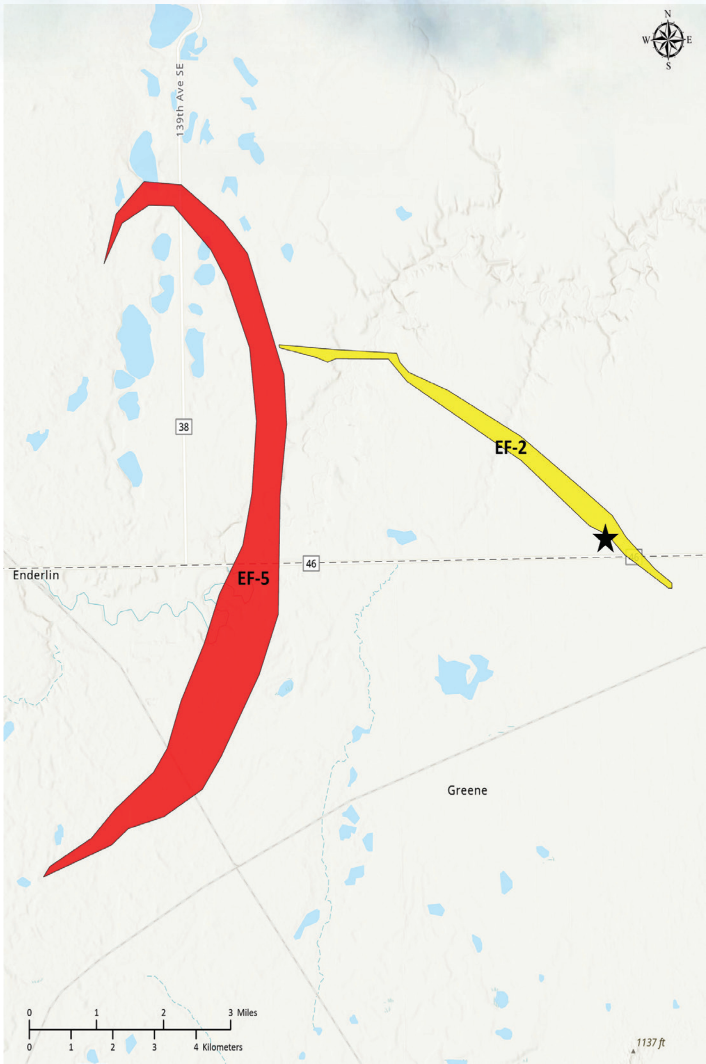

FIGURE 1.
The Map displays tornado paths in the Enderlin area. The black star is the primary location where the NDGS assisted with cleanup. Adapted from https://www.weather.gov/media/fgf/Enderlin.pdf (retrieved October 31, 2025).

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FIGURE 2.
UAS image of volunteers cleaning debris from fields, view is to the northwest. The location is east of Enderlin on the site highlighted in figure 1.

FIGURE 3.
UAS image of devastation caused by the EF-2, view is to the northwest. The location is east of Enderlin on the site highlighted in figure 1. Of note, in the upper portion of the UAS image, clear ground scarring caused by the tornado is visible (see black arrow at midpoint).

LOOKING BEYOND GIANTS

A Brief Creaming Curve Perspective for Post-Bakken/Three Forks Exploration in the Williston Basin, North Dakota

BY ISMAIL FARUQI

In early 2025, North Dakota enacted House Bill 1483, a new law aimed at encouraging oil and gas activities beyond the Mississippian-Devonian Bakken and Three Forks Formations across the Williston Basin, North Dakota. From a basin-wide perspective, this raises a timely question: What lies beyond the Bakken/Three Forks? Which formations and fields have historically shown promise? And what lessons from these past developments might help identify new exploration opportunities?

Nesheim (2024) summarized recent non-Bakken/Three Forks drilling activity over the past decade, highlighting the limited exploration outside these dominant plays mainly because of the operators' appetite for the well-established and low-risk Bakken/Three Forks play. The creaming curve for the North Dakota portion of the Williston Basin (fig. 1) illustrates that since the 1920s, approximately 40,000 oil and gas wells have been drilled across the Williston Basin, yielding a cumulative hydrocarbon production of around eight billion barrels of oil equivalent (BOE) from multiple formations (NDOGD, 2025). Of this total, more than six billion barrels of oil equivalent has been produced from the Bakken/Three Forks play alone.

While the post-2006 Bakken boom accounts for the majority of this Bakken/Three Forks production, the creaming curve reveals two distinct phases of heightened oil and gas activity that helped shaped North Dakota's roughly two billion barrels of oil equivalent of non-Bakken/Three Forks hydrocarbon output. During the 1950s and 1960s, activity was mostly driven by vertical exploration drilling targeting

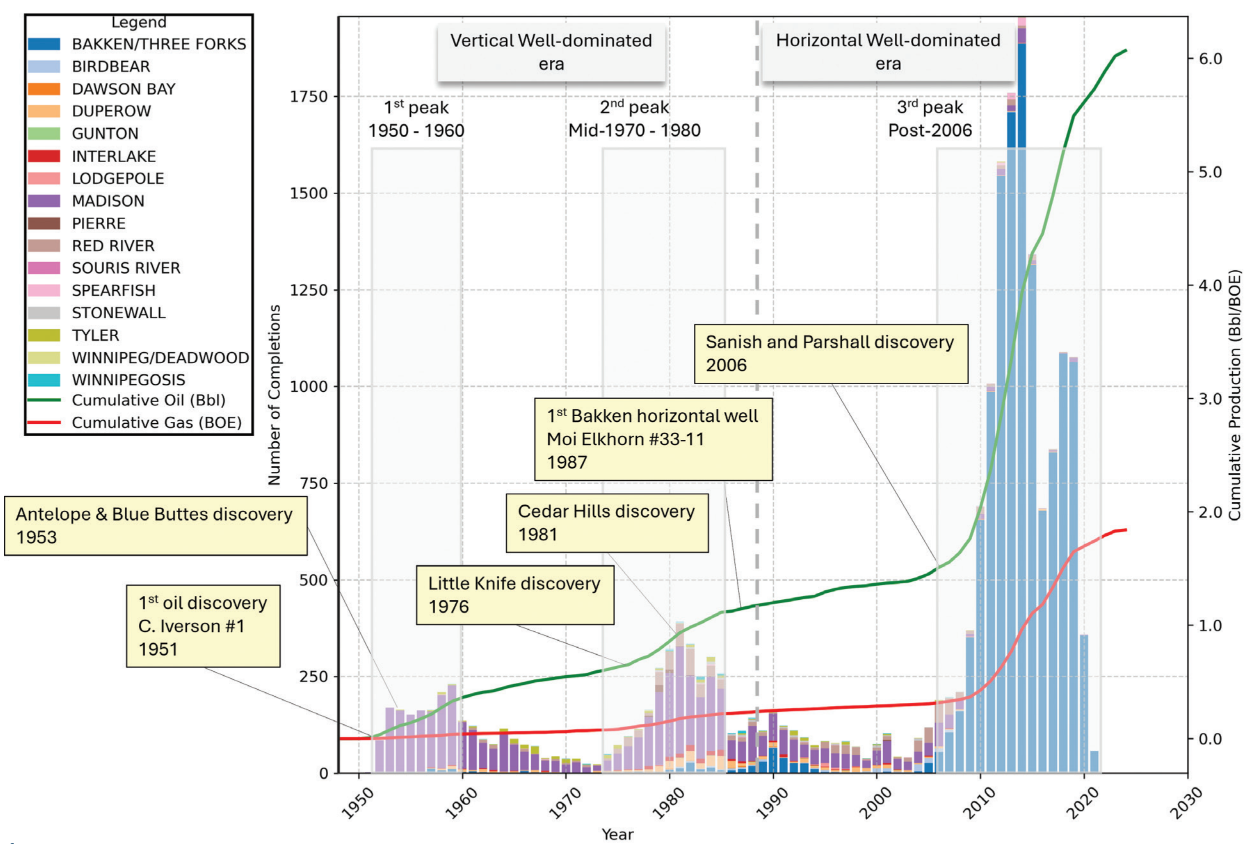

FIGURE 1.
Creaming Curve of Williston Basin. X-axis showing completions' year, first Y-axis on the left shows number of completions, second Y-axis on the right shows cumulative hydrocarbon production in Bboe. Bar graph colored based on formation.

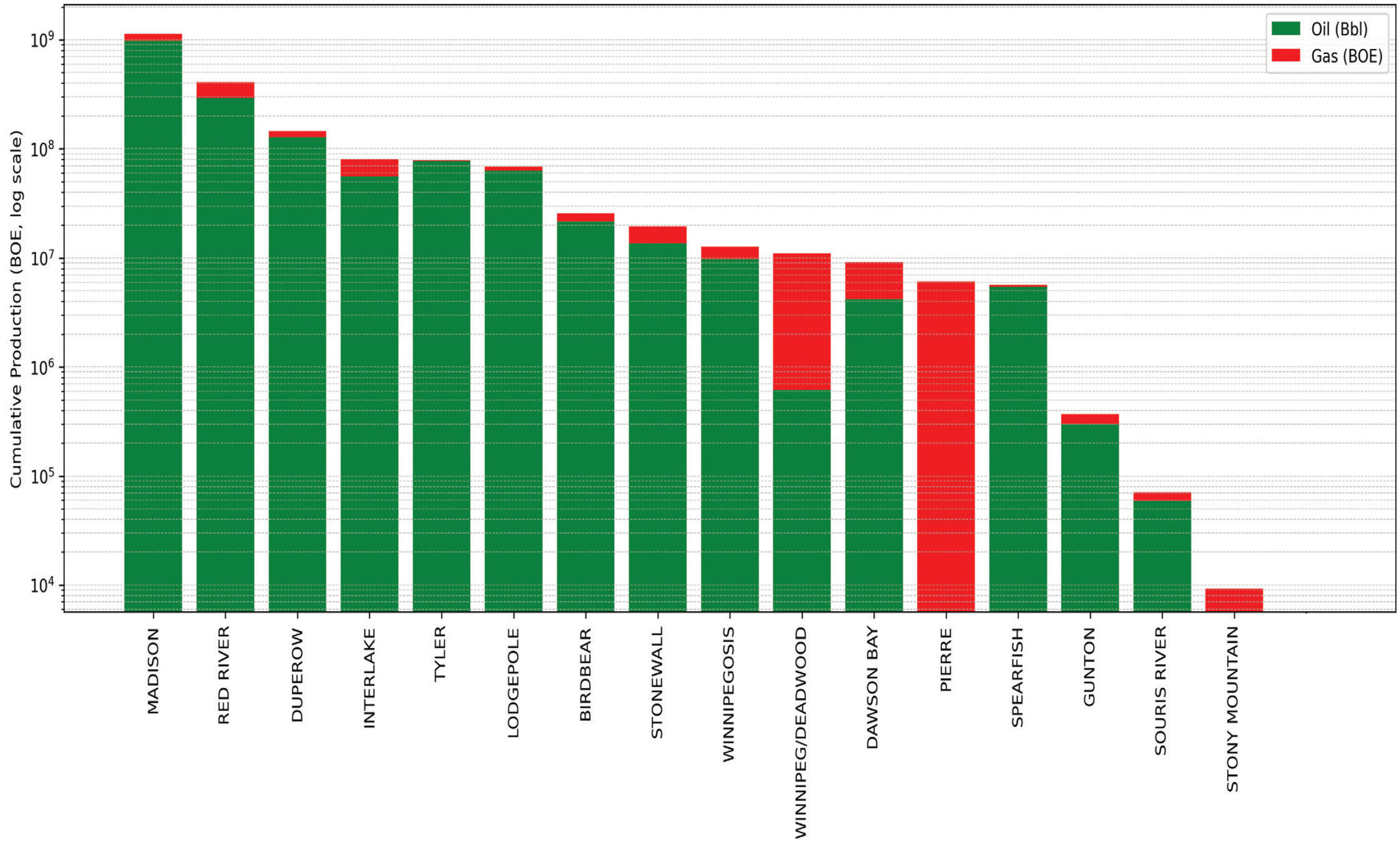

FIGURE 2.
Cumulative oil and gas production by formation, excluding the Bakken/Three Forks Formations, with log scale in barrels of oil equivalent. Green for oil, red for gas.

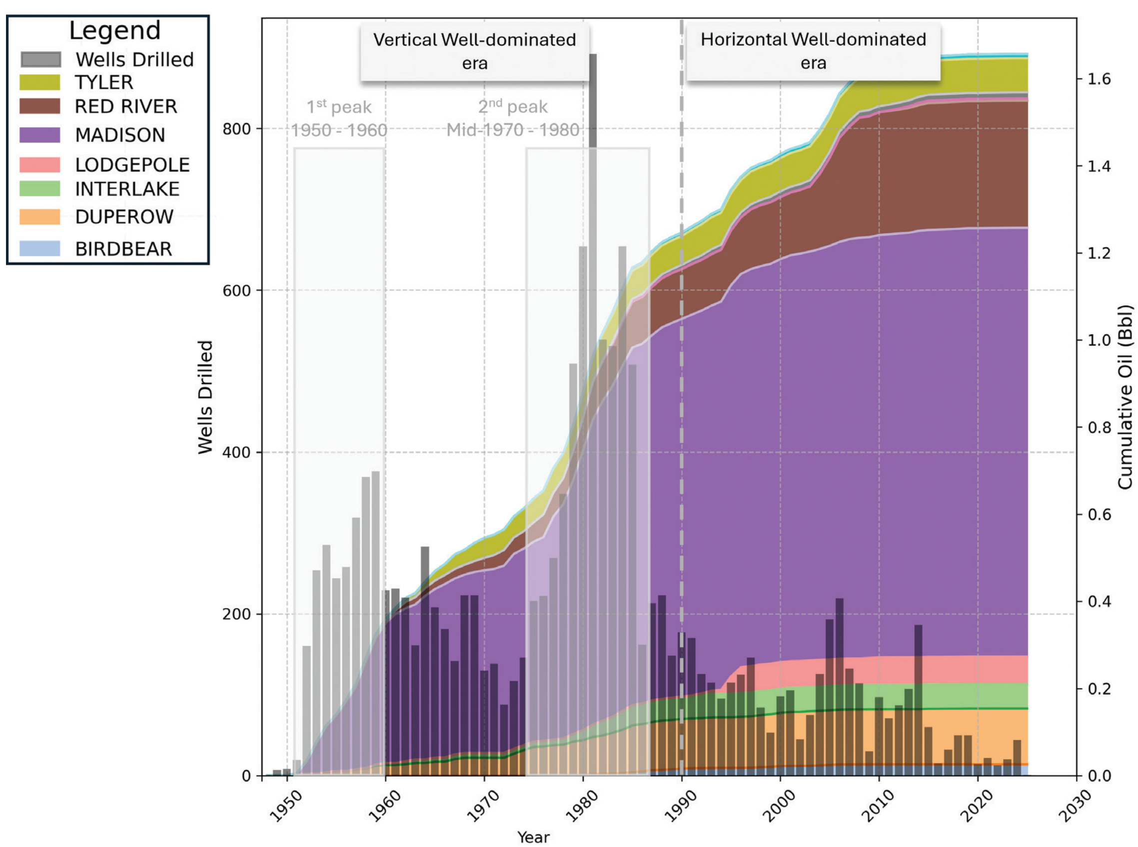

FIGURE 3.
Stacked cumulative oil colored by formation (excluding Bakken/Three Forks Formations). The bar chart displays the number of wells drilled.

conventional reservoirs primarily from the Madison Group's oolitic limestone along the Nesson anticline (Folsom et al., 1959). From the mid-1970s to mid-1980s, most completions continued within the Madison Group, with a key addition in the Ordovician Red River Formation. During this period, new large fields were also discovered along structural features such as the Little Knife Anticline and the Billings Anticline.

The creaming curve also highlights how production evolved over time and which geologic formations have been most significant. Among these, the Madison Group leads with more than one billion barrels of oil equivalent produced (fig. 2). The Red River and Duperow Formations follow, contributing over 400 million and 100 million barrels of oil equivalent, respectively. The Interlake, Tyler, and Lodgepole Formations follow with cumulative oil and gas production just shy of 100 million barrels of oil equivalent.

As shown in the stacked non-Bakken/Three Forks creaming curve in figure 3, several noticeable inflection points reflect significant contributions to cumulative oil production from outside the Bakken/Three Forks Formations, which mainly occur prior to the 2006 Bakken boom.

In the 1960s, formation-level contributions began to diversify beyond the Madison Group and Duperow Formation. By the mid-1970s, several notable field discoveries, such as Little Knife and Big Stick (fig. 4), led to a sharp increase in production from the Madison Group. In the early 1980s, discoveries like the Cedar Hills Field in 1981, marked a major uptick in Red River Formation output. The Lodgepole Formation also saw a sharp production surge in the 1990s, following Conoco's discovery of a reefal mound reservoir during a deep test in the Dickinson Field (Burke and Diehl, 1995). The most recent substantial boost came from a jump in Red River Formation production between 2000 and 2009. Since the early 2010s, however, production from non-Bakken/Three Forks intervals has largely plateaued.

At the field level, several standout non-Bakken/Three Forks fields have emerged as dominant contributors to the basin's production history. Figure 4 displays the top 10 oil fields ranked by cumulative production. Most of these top fields are associated with the Madison Group. Interestingly, the number one producing oil field in the basin, the Cedar Hills Field, stands apart due to its lack of Madison Group production. The Cedar Hills Field produces exclusively from the Red River Formation, and with cumulative oil production of approximately 150 million barrels, it accounts for nearly 50% of the Red River Formation's total cumulative output (Nesheim, 2017b).

The creaming curve, combined with statistical data on North Dakota's most productive non-Bakken/Three Forks Formations and oil fields, offers insights into both historical success and future exploration opportunities.

First, major hydrocarbon discoveries tend to coincide with

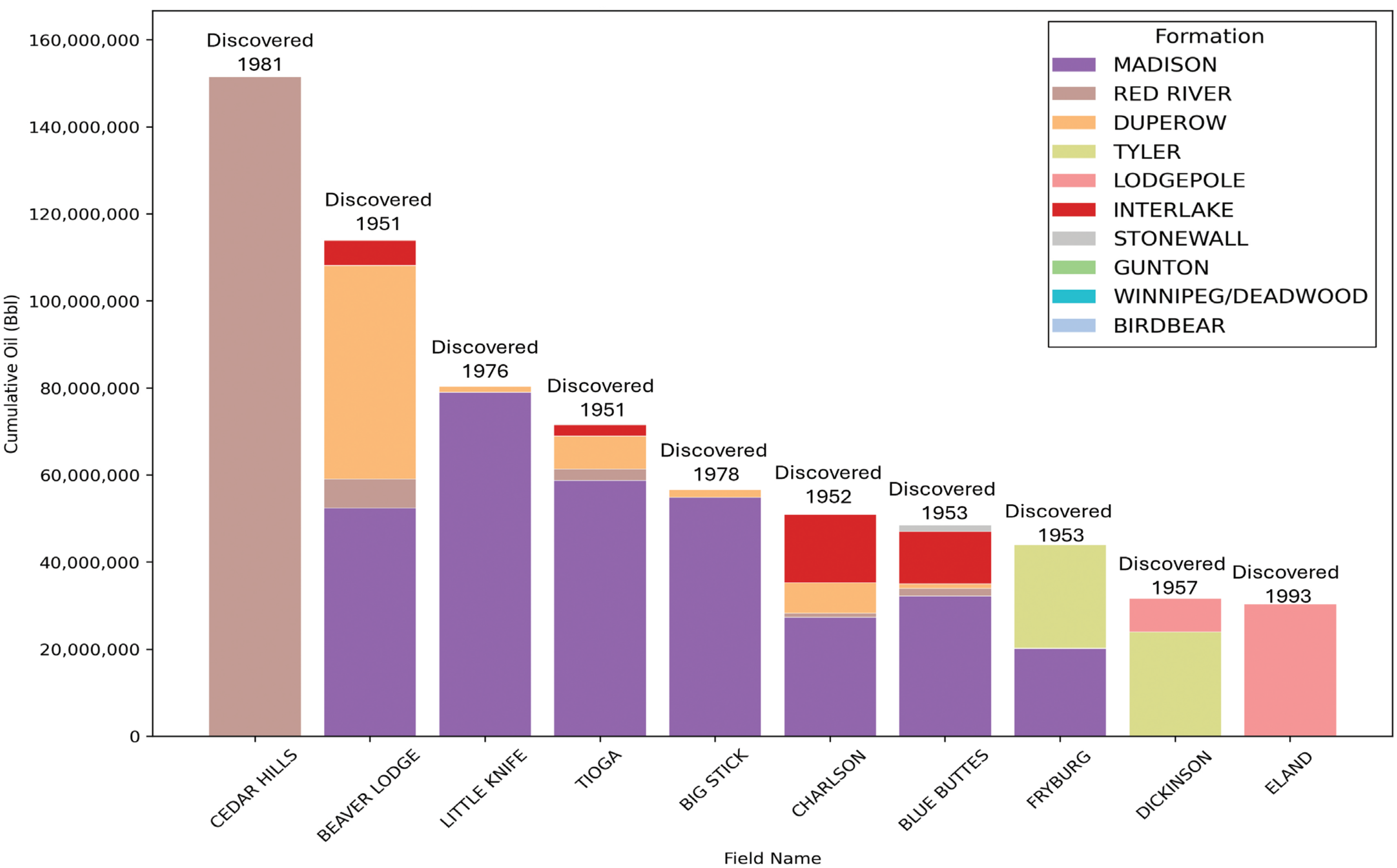

FIGURE 4. Top 10 fields by cumulative oil production in barrels along with its discovery year. Graph colored based on formation contribution, excluding the Bakken/Three Forks Formations.

periods of intense drilling activity. Almost all of the top 10 oil and gas fields in the Williston Basin from the non-Bakken/Three Forks were discovered during the peak phases: the 1950s–1960s and the mid-1970s to mid-1980s. These trends suggest that when a new play is unlocked, whether through improved geological understanding or technological advancement, and paired with strong economic drivers, it can set the stage for the next huge discovery of oil and gas fields.

Second, several major fields have demonstrated significant production outside the Bakken/Three Forks system. The Madison Group and Red River Formation rank next in cumulative hydrocarbon contribution, highlighting the opportunity to revisit these intervals. This could involve applying established concepts in new areas or introducing new exploration strategies in both mature and frontier zones. For instance, are there bypassed zones within the Madison Group along basin margins, beyond historically saturated areas? Could the Red River Formation, outside the prolific Cedar Hills Field, offer untapped potential through alternative trap styles or in emerging areas of southwestern and northwestern North Dakota (Nesheim, 2017a)?

From a spatial and stratigraphic perspective, it is worth considering whether hydrocarbon accumulations may exist in established fields but within different formations. For example, the Eland Field currently produces solely from the Lodgepole Formation, while its neighboring Dickinson Field has significant production from the Tyler Formation (fig. 5). This raises a question: could the Tyler Formation hold untapped hydrocarbon potential in the Eland Field? Similarly, fields such as Little Knife, Big Stick, and Fryburg show no recorded production from the Red River Formation; yet they might lie within a region of interest. Nesheim (2017b) noted that fields extending from Billings County down to Slope County may hold promises for Red River Formation exploration, as they coincide with the kukersite-rich intervals and fall within the mapped Red River Formation hydrocarbon migration fairway. Supporting this, Whiteman et al. (1998) described the Cedar Hills Field, primarily producing from the Red River "B" interval, as lacking structural closure, with field limits controlled more by economic cutoffs than geologic boundaries, suggesting that reservoir extension with hydrocarbon column opportunities may still exist.

While this analysis isn't a definitive roadmap for future exploration, it offers a useful lens to reflect on nearly 75 years of drilling activity since the discovery of North Dakota's first oil well, and how trends, new plays, and evolving technologies have shaped oil and gas discoveries. The creaming curve helps tell that story; showing when key fields were discovered, what formations were delivered, and when things really took off. Many of the basin's top-producing fields were uncovered during these active phases, showing the value of intense exploration and development activities. There's still value in revisiting proven plays with fresh ideas and better tools on the rocks.

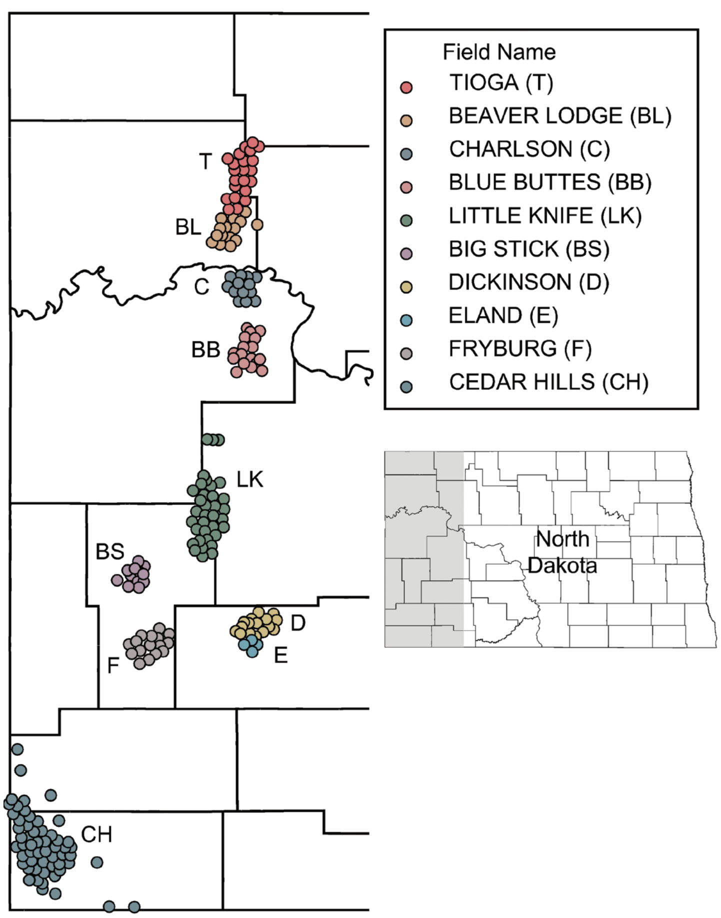

FIGURE 5.
Spatial distribution of well completions in top 10 oil fields.

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Tim Nesheim Receives AAPG Award

BY JEFF PERSON

Timothy (Tim) Nesheim received the 2025 John D. Haun Landmark Publication Award for his paper titled "*Stratigraphic and geochemical investigation of kukersites (petroleum source beds) within the Ordovician Red River Formation, Williston Basin.*" This paper was published in 2017 through the American Association of Petroleum Geologists (AAPG) Bulletin. The award was presented at the 2025 Rocky Mountain Section AAPG Annual Meeting that was held in Keystone, CO during October 5-7.

In addition to the author, three former subsurface geologists from the North Dakota Geological Survey were noted to have contributed to the publication. Jeff Bader was instrumental with the sample collection phase of the study as well as an early thorough review of the manuscript. Julie LeFever and Stephen Nordeng were also recognized for providing discussion and early guidance with the study.

ABOUT THE AWARD

The John D. Haun Landmark Publication Award recognizes the authors or editors of a book, guidebook or other publication that over the past decade has had exceptional influence on developing new hydrocarbon plays or deeper understanding of fundamental geology within the Rocky Mountain region. This award was first issued in 2013 and is named in honor of Dr. John D. Haun, who was a longtime Rocky Mountain geologist and past president of the AAPG and AIPG. Multiple nominations are made each year, and one selection is made by the elected officers of the Rocky Mountain Section AAPG.

SIGNIFICANCE OF THE PAPER

Of the numerous geologic formations that have commercially produced oil and gas in North Dakota, the Red River Formation is the third most productive interval behind the prolific Bakken-Three Forks Formations and the Mississippian Madison Group reservoirs. To date, more than 1,400 vertical and horizontal wells have combined to produce over 360 million barrels of oil and 783 billion cubic feet of gas from the Red River Formation in North Dakota.

Older published studies concluded that oil and gas in Red River reservoirs originated from the underlying Icebox Formation (Dow, 1974; Williams, 1974). Meanwhile, research in Saskatchewan's portion of the Williston Basin indicated that the Red River contains its own organic-rich, oil and gas generating mudstone layers (Osadetz and Snowdon, 1995; Stasiuk and Osadetz, 1990; Fowler et al., 1998). The award-winning paper by Tim Nesheim mapped out the extent of the Red River kukersites across western North Dakota using a combination of core samples and wireline logs and calculated an estimated hydrocarbon generation volume of 27 to 62 billion barrels of oil equivalent. This research highlighted an underexplored portion of the Red River petroleum system that spans multiple counties in southwestern

North Dakota (Nesheim, 2017). Understanding the approximate amount and the distribution of oil and gas generated within the Red River petroleum system is one large step toward further unlocking additional hydrocarbon resources from the unit.

ABOUT THE AUTHOR

Tim Nesheim has worked for the North Dakota Geological Survey as a subsurface geologist since 2010. He was promoted to Head of the Subsurface Section in 2017 and Manager of the Wilson M. Core and Sample Library in 2022. His research has spanned multiple sedimentary formations across the Paleozoic section of North Dakota's Williston Basin with a focus on petroleum systems. In addition, Tim's research has been acknowledged by the Best Paper A.I. Memorial Levorsen Award for his presentation titled "*Examination of source rocks within the Tyler Formation (Pennsylvanian), North Dakota*" from the 2012 RMS-AAPG Annual Meeting, and the 2022 Best Paper Award in The Mountain Geologist (Rocky Mountain Association of Geologists) for his paper titled "*Preliminary identification and evaluation of petroleum source beds within the Mississippian Madison Group: A step toward redefining the Madison petroleum system of the Williston Basin.*"

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A BASIC UNDERSTANDING OF NORTH DAKOTA'S SURFACE AND BEDROCK GEOLOGY

BY FRED J. ANDERSON

Before planning any large-scale infrastructure projects in North Dakota, understanding the basic architecture of North Dakota's geology is fundamental. Simply stated, there are two main types of rocks and sediments that are exposed at the surface in North Dakota: sedimentary bedrock and glacial deposits. Sedimentary bedrock is found exposed in the southwest quarter of the state and comprises our topographically majestic buttes and high-relief badlands landscape. This bedrock contains bedded sandstones, siltstones and mudstones, of marine and terrestrial origin, the latter is interbedded with coal. Glacial deposits cover the rest of the state. This blanket of glacial sediment (what geologists commonly call till) generally consists of a variable mix of clay, silt, sand, and gravel mixed with occasional boulders (fig 1). These deposits cover 50,760 square miles (131,468 km^2) of the northern, central, and eastern parts of the state and are often the youngest and first deposits encountered at the land surface (fig. 2). The southwestern part of the state is generally devoid of glacial deposits except for localized remnants of till and the scattered glacial erratic boulders that mark the limit of glacial advance in southwestern North Dakota (fig. 3).

FIGURE 1.
Glacial deposits like these found just east of Minot, commonly called till, are found across most of the North Dakota landscape. In this photo the mixed nature of these deposits can be readily seen. Geologists specifically use the term "Diamicton" to describe this type of deposit that consists of a mixture of poorly sorted sediment that contains a variety of grain sizes such as sand, pebbles, cobbles, and boulders, within a fine grained (mud) matrix that originated from the scouring action beneath a glacier. Red-orange iron staining is evidence of shallow groundwater flow along fracture planes in the till.

Glacial deposits generally thicken from the southwest to the northeast across the state and can be thicker within major glacial meltwater valleys. They are also thicker across a band trending from the northwest to the south-central part of the state which follows the topographic expression of the Missouri Couteau and the Red River Valley (fig. 2). These sediments were deposited when glacial ice advanced as many as 15 or more times across the state during the ice age around 2.6 million - 10,000 years ago (Clayton and others, 1980b). These deposits comprise the Coleharbor Group initially named the Coleharbor Formation (Bluemle, 1971). It was subsequently suggested for promotion to Group status the following year by Clayton (1972) with his work on the geology of Mountrail County.

Eventually the Coleharbor Formation was expanded to the larger Group status in 1980 with the publication of the Geologic Map of North Dakota and accompanying explanatory text (Clayton and others, 1980). Glacial deposits of the Coleharbor Group directly underlie 73% of the state's population, more than any other stratigraphic unit. Therefore, its importance as a geologic unit, particularly when it comes to considering new locations for energy and civil infrastructure projects, must not be overlooked.

Sedimentary bedrock, notably shales of the Pierre Formation, is also exposed at the land surface in and along major river valleys in eastern North Dakota, such as the Pembina Gorge and along the Sheyenne River valley. There is no bedrock older than the Cretaceous Greenhorn Formation exposed in North Dakota, which outcrops only in very localized areas within the Pembina Gorge in the northeastern corner of the state. Since the younger glacial deposits lay directly on top of much older bedrock (what geologists call an unconformity) across much of the state (fig. 4) the thickness of these deposits is often equal to the depth to the bedrock (fig. 2).

Knowledge of the landscape and the basic relationship between the surface and bedrock geology in North Dakota is fundamental for those contemplating large construction and infrastructure projects, such as pipelines and energy facilities. Knowledge of geology in the glaciated and non-glaciated parts of the state provides planners and engineers with a better understanding of the subsurface conditions likely to be encountered. This also facilitates proper selection of the best available and most appropriate geologic information to use when planning large projects. For example, improper selection of a statewide bedrock map or data set in place of a surficial geologic map for pipeline route analysis could lead to erroneous conclusions along the route. Contacting NDGS geologists early in the planning process is prudent.

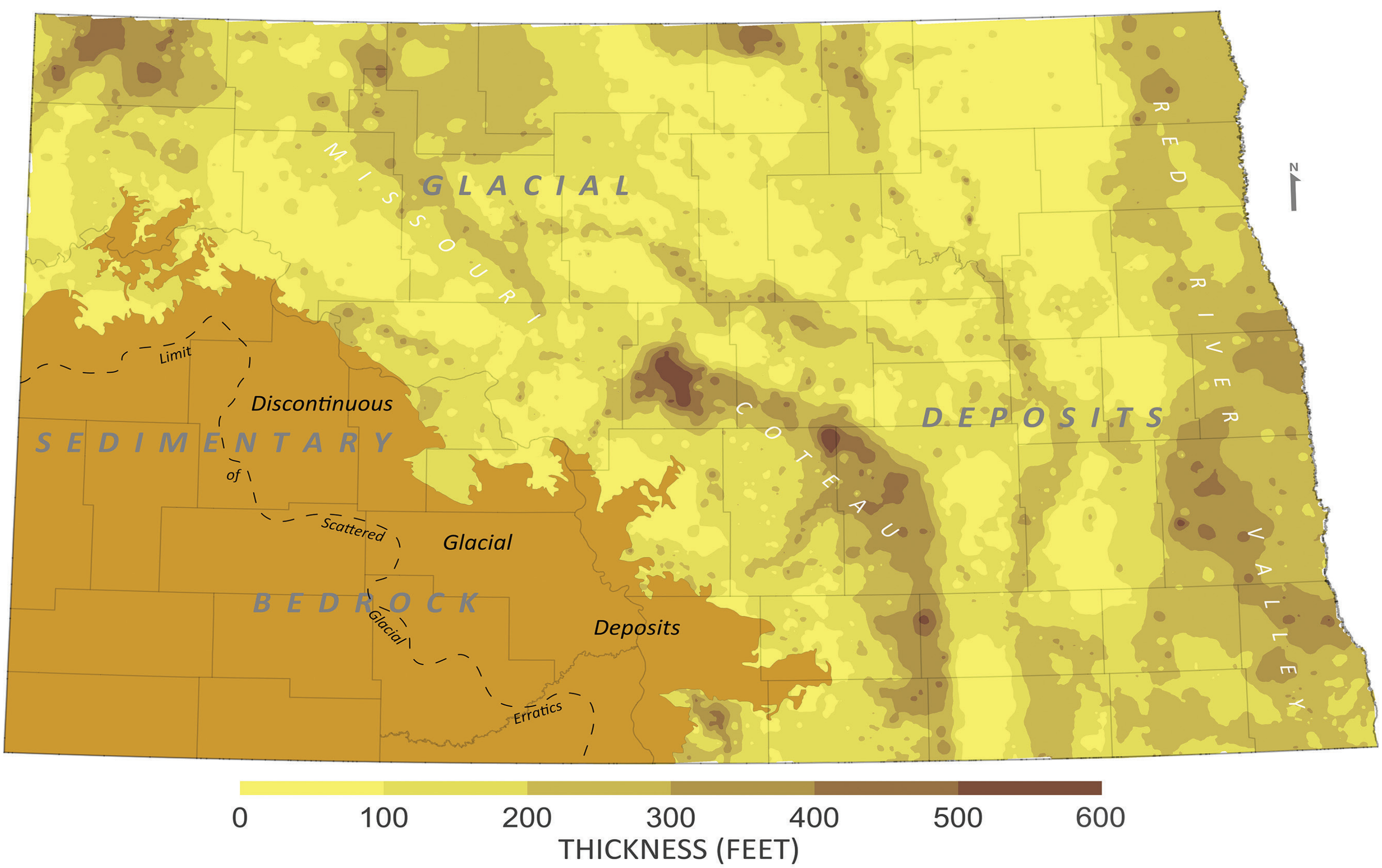

FIGURE 2.
Isopach (thickness) map of contiguous surficial glacial deposits across North Dakota modified and modeled from publicly available water-well drilling records data. These deposits blanket over three-quarters of the state. Localized glacial deposits may be found scattered within the area to the southwest bounded by the limit of scattered glacial erratics.

FIGURE 3.
Glacial erratic boulders like these, found in a rockpile just west of Mandan near Crown Butte in Morton County, can be found scattered across southwestern North Dakota marking the extent of glaciation in the state during the Ice Age.

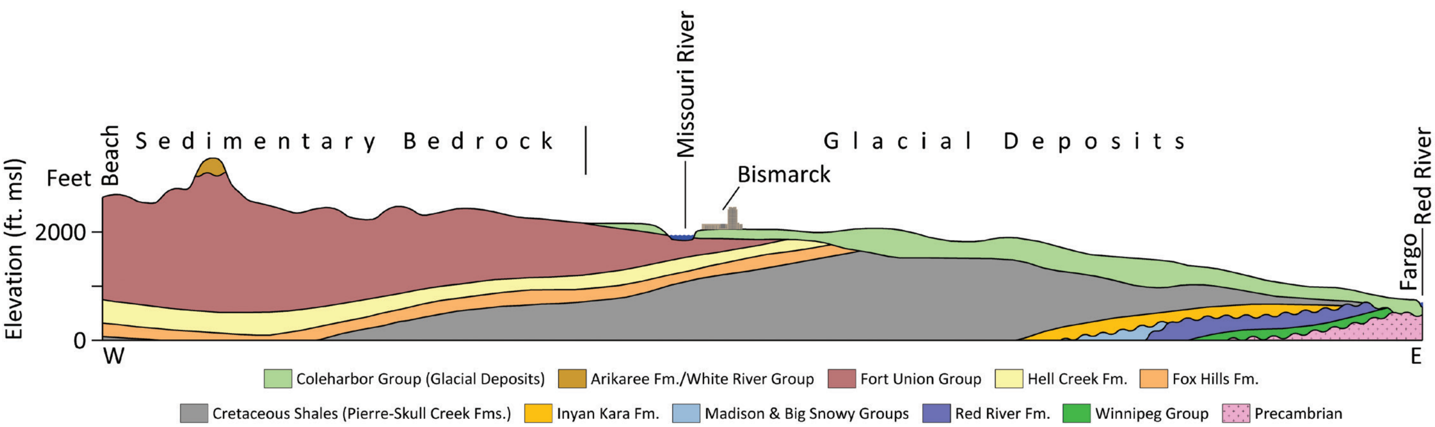

FIGURE 4.
West to east diagrammatic cross section across North Dakota approximately along ND Highway 200 illustrating the relationship of glacial deposits and underlying shallow bedrock as found occurring above sea level elevation. Glacial deposits blanket the bedrock layers that dip towards the west forming the eastern flank of the Williston Basin.

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SATELLITE SIGHT

Monitoring North Dakota Landscapes from Space

BY JORDAN DAHLE

With the launch of the recent NISAR (**N**ASA-**I**SRO **S**ynthetic **A**perture **R**adar) Mission (fig. 1), a collaborative effort of the National Aeronautics and Space Administration (NASA) and the Indian Space Research Organization (ISRO), there is renewed interest in the potential applications of remote sensing for North Dakota (NASA, 2025b). Earth observation satellites provide datasets that are useful in a variety of scientific pursuits, including meteorology, ecology, and geoscience. These satellites are equipped with one or more remote sensing systems that can be grouped into two categories:

Passive Remote Sensing

Passive remote sensing techniques rely on sensors that detect signals emitted from or reflected by an object. For example, Landsat satellites carry sensors that detect sunlight reflected by Earth's surface. The multispectral sensors measure the amount of light reflected within discrete bands, or ranges, of visible and infrared light, measured in wavelengths (fig. 2). As these sensors rely on sunlight to illuminate Earth's surface, the satellites typically have a sun-synchronous orbit. This orbital path keeps the satellite within the illuminated portion of Earth's surface, passing over a given area at the same local time each day.

Active Remote Sensing

Active remote sensing techniques use systems that emit their own signal to scan an object. The signal is then reflected by the object and the sensor measures that reflected signal. The synthetic aperture radar (SAR) sensors on the NISAR satellite are a type of active remote sensing. SAR sensors emit radar pulses that are reflected in all directions by Earth's surface, and the portion of the signal that returns to the sensor is recorded for each pixel in terms of wavelength amplitude and phase. This "backscattered" signal received by the SAR system is used to measure the distance between the sensor and Earth's surface in the line of sight (LOS) direction.

Synthetic Aperture Radar (SAR)

SAR satellites are generally polar-orbiting, and capture data when travelling in both ascending (south to north) and descending (north to south) directions (fig. 3). NISAR will cover the entirety of Earth's surface twice every 12 days, once ascending and once descending, transmitting its collected data daily (NASA, 2025a).

The wavelengths of the radar pulses used by SAR instruments are grouped into bands: X-band (2.4-3.8 cm), C-band (3.8-7.5

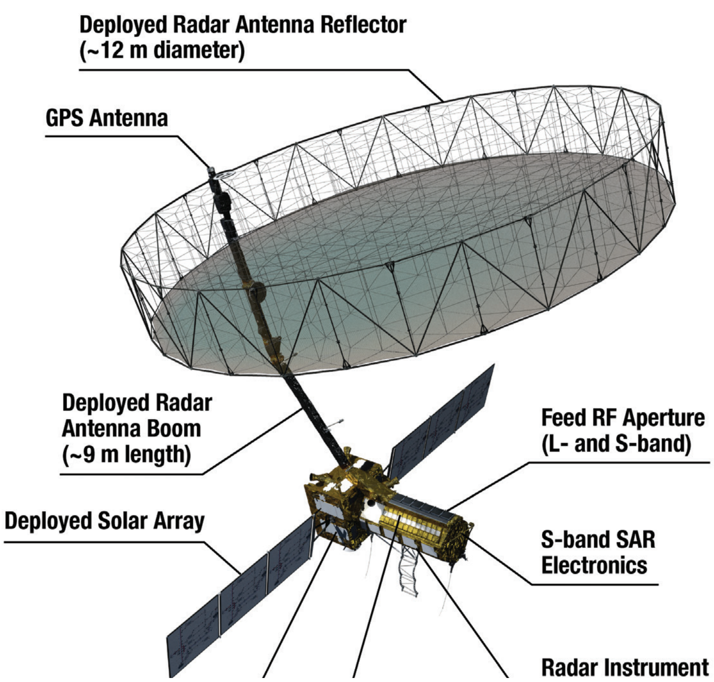

FIGURE 1.
Artistic rendering of the NISAR satellite with primary components and systems labeled. The NISAR mission successfully launched on July 30th, 2025, from the Satish Dhawan Space Centre in southeast India. The first 90 days of the mission were dedicated to commissioning, while NASA and ISRO teams completed system checks and calibrated instrumentation. (Source: NASA, 2025a)

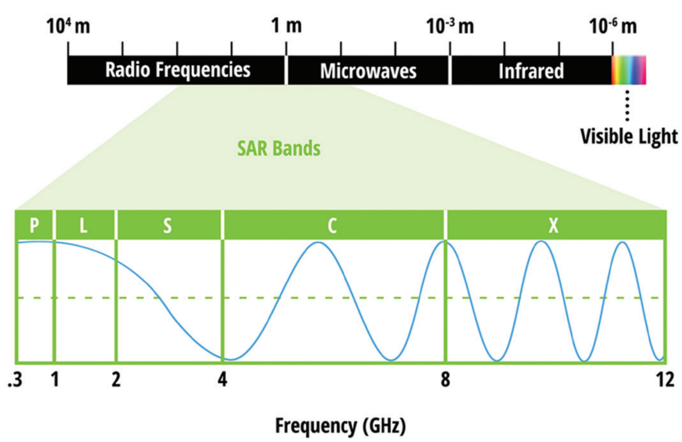

FIGURE 2.
This section of the electromagnetic spectrum highlights frequently used SAR bands, falling within the Microwave frequency range. The lower (green) section depicts their frequencies, showing that as wavelengths decrease, frequency increases. Infrared and visible light, the types of radiation detected by Landsat, have much shorter wavelengths and therefore higher frequencies than SAR bands. (Source: Earthdata, 2025)

cm), S-band (7.5-15 cm), L-band (15-30 cm), and P-band (30-100 cm) (fig. 4). The wavelength of radar emitted determines how the pulses interact with Earth's surface. For example, X- and C-band radar pulses cannot penetrate dense vegetation, while L- and P-bands are capable of penetrating much denser vegetation. SAR wavelength is also related to vertical resolution, with shorter wavelengths resulting in higher vertical resolution.

In recent decades, C-band SAR satellites (e.g., Sentinel-1) have been heavily relied on for global change detection seen as a balance between high resolution and moderate vegetation penetration (Meyer, 2019). The NISAR satellite is equipped with dual S- and L-band SAR instruments (10 and 24 cm), which will produce data with 3- to 10-meter spatial resolution (ISRO, 2025).

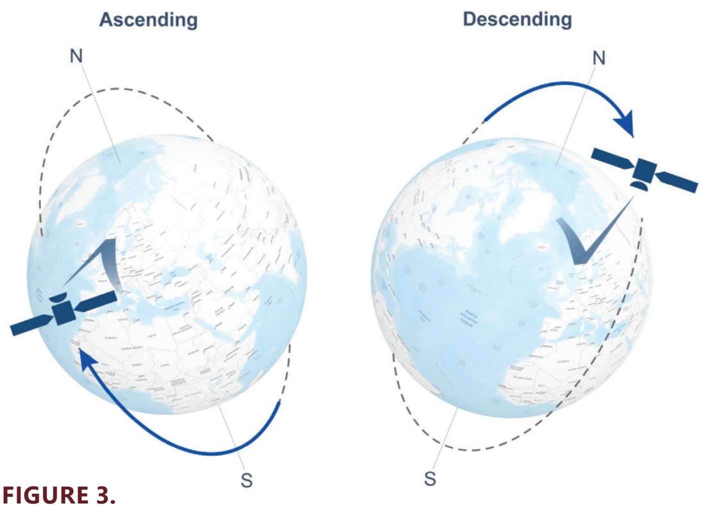

FIGURE 3.
Polar orbiting satellites pass above Earth's poles, travelling at near North-South trajectories. In this orbit, satellites are able to provide global coverage. SAR systems aboard polar orbiting satellites acquire data in both the ascending (south to north) and descending (north to south) directions. (Source: NGU, n.d.)

Interferometric SAR (INSAR)

While individual SAR acquisitions can be useful for mapping Earth's surface, interferometric synthetic aperture radar (InSAR) allows for the examination of surface deformation through time using multiple SAR acquisitions (fig. 5). InSAR methods combine multiple SAR acquisitions over an area of interest. Pairs of SAR images (reference and secondary) are processed to create interferograms, where each pixel represents the phase difference between the two original SAR images (Meyer, 2019). The difference in phase between the reference and secondary SAR images corresponds to the change in line of sight distance between the sensor and Earth's surface.

Interferograms can be used to quantify the surface deformation caused by both instantaneous and continuous events. SAR image pairs selected from before and after an earthquake or catastrophic landslide, for example, can reveal the resulting surface displacement. A series of SAR image pairs could also be examined together to measure cumulative displacement for slow or continuous processes, such as slope deformation, subsidence, glacier recession, and even magma chamber inflation/deflation (Li et al., 2022).

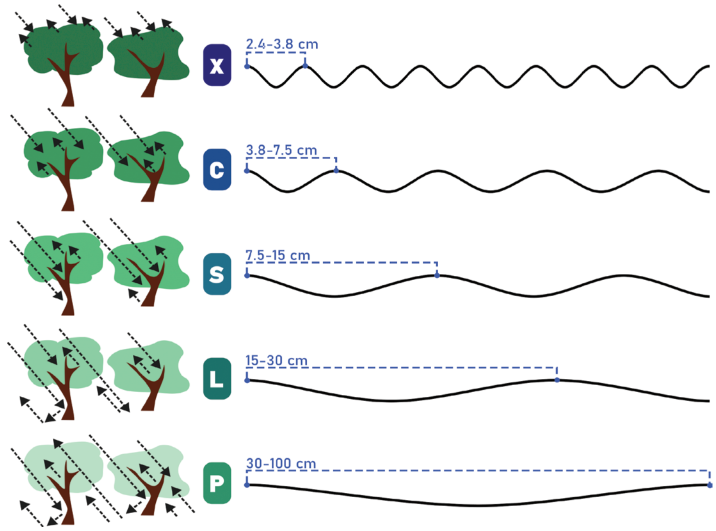

FIGURE 4.
At shorter wavelengths, radar pulses are scattered by the surface of the vegetation canopy (e.g., leaves and small branches), providing information about the canopy structure. At longer wavelengths, radar pulses pass through the canopy to reach the ground beneath, providing information about the ground surface. Modified from Meyer (2019) and https://storymaps.arcgis.com/stories/20d8cd2ce11a4d5d81a8a65711d5ec29 (retrieved October 1, 2025).

SAR Opportunities

When considering the potential applications of SAR data, it is crucial to recall that SAR images capture the surfaces that reflect the emitted radar pulses. Surface water bodies are poor reflectors of all SAR wavelengths, thus inundated areas stand out from the surrounding terrain, enabling flood and water-level monitoring (e.g., Schlaffer et al., 2022). Shorter wavelength SAR bands (X- and C-bands) are reflected by vegetation, as a result, they provide invaluable datasets for land cover and agricultural classification (e.g., Whelen and Siqueira, 2018; McNairn et al., 2018). When the aim is to capture ground surface deformation, longer wavelength SAR

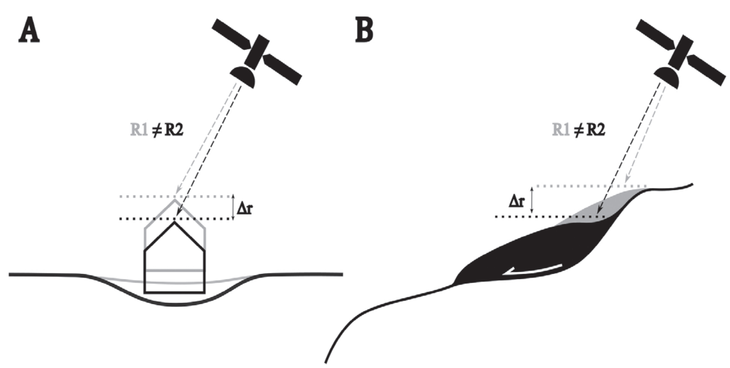

FIGURE 5.
InSAR methods can be used to measure changes in the distance between the ground surface and the SAR sensor, called range distance (R), using SAR images acquired at different times. This difference in range distance, measured along the sensor's line of sight, is represented above by Δr. **A**) In this example, a home has moved vertically due to subsidence, resulting in an increase in range distance. **B**) Here, a landslide has occurred, resulting in vertical and horizonal motion. Upslope portions of this landslide would show increases in range distance, while downslope portions may show decreases in range distance. Modified from NGU (n.d.).

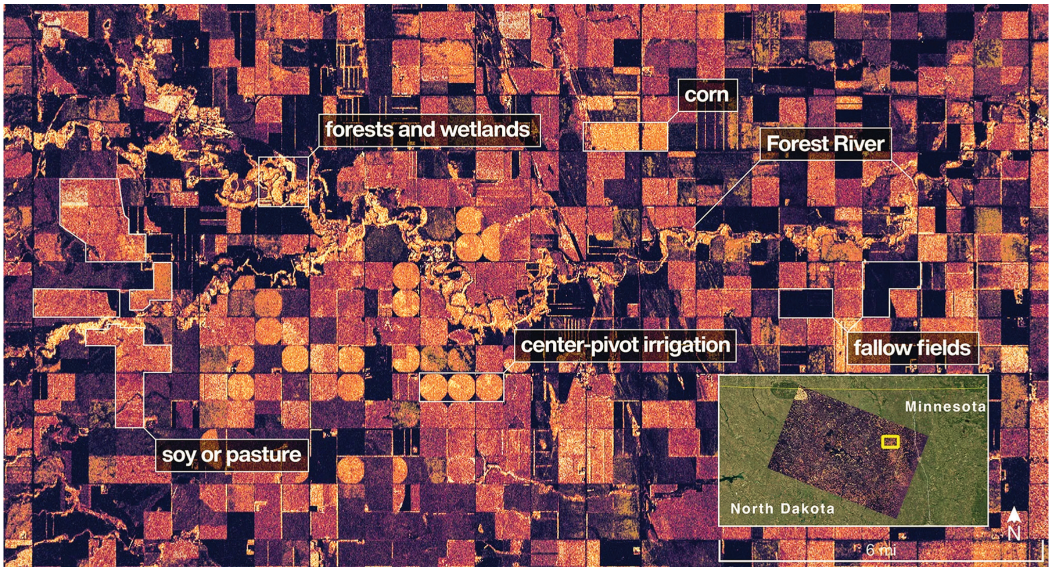

FIGURE 6.

On Sept. 25th, 2025, NASA released the first images from the NISAR satellite. One of the two locations selected for the press release was northeastern North Dakota, centering on a segment of the Forest River near Fordville. The location map in the lower right corner shows the scale of the full SAR image captured, while the area highlighted in yellow is shown in detail in the main image. This annotated satellite image highlights potential agricultural applications, demonstrating how land use can be inferred from SAR imagery. (Source: NASA, 2025b)

bands (L- and P-bands) enable ground surface deformation monitoring in regions with more dense vegetation cover (e.g., Schlögel et al., 2015). As a new source of L-band SAR data, NISAR presents an opportunity for surface deformation monitoring in regions of North Dakota with higher vegetation density (fig. 6).

SAR Limitations

Though the opportunities presented by the NISAR mission are exciting, it is important to note the limitations of SAR data and InSAR methods. The spatial resolution of SAR data is a primary limiter to its applicability in many cases. Where available, LiDAR data will provide significantly higher spatial resolution. However, LiDAR data is generally more expensive and time consuming to acquire. North Dakota has statewide LiDAR coverage with 1 to 2-meter resolution (see https://www.dmr.nd.gov/dmr/ndgs/lidar-maps). Existing LiDAR datasets have been invaluable tools for ongoing NDGS landslide mapping efforts.

InSAR applicability is also limited by topography and direction of surface deformation. The polar orbital path of NISAR and other SAR satellites means that they have very limited sensitivity to surface deformation in the north-south direction. SAR sensors are side-looking, so their sensitivity is highest to deformation perpendicular to their near north-south flight path (van Natijne et al., 2022).

Environments with significant seasonal variation pose additional challenges to the application of InSAR methods. Changes in environmental characteristics, such as snowpack and vegetation density changes, impact how the radar pulses are reflected by Earth's surface. When these changes are rapid or significant, InSAR methods may not be successful. With the knowledge of the existing opportunities and limitations, the North Dakota Geological Survey is evaluating ways to incorporate this upcoming dataset to enhance ongoing projects.

Data Access

NISAR data will be hosted by NASA's Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC) and made available through their public data search tools (e.g., ASF Vertex; https://search.asf.alaska.edu).

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From MESA to MORAINE

THE GEOLOGIC TRANSFORMATION OF THE TURTLE MOUNTAINS

BY BENJAMIN YORK

Imagine you are a young 1800s fur trader making your way from Hudson Bay to the Missouri River. You left your native England and have been traveling through endless miles of dense Canadian forest filled with black spruce and trembling aspen. After reaching what is now Lake Winnipeg you make your way to the Assiniboine River hoping the hardest part of your journey is done. Traveling west along the Assiniboine you eventually leave your boat for the last leg of the journey before reaching the Missouri River. You have never seen this bit of land between the Assiniboine and Missouri Rivers before, and there is one feature that dominates your view for miles as you travel further south. Across the southern horizon is a low rise that reminds you of an upturned bowl, or possibly a turtle shell (fig. 1). You are not the first European to experience this out-of-place "mountain," and you won't be the last.

The Turtle Mountains rise 600 - 800 feet above the surrounding landscape and are dominated almost entirely by collapsed glacial topography (fig. 2) (Bluemle, 1986). This higher elevation compared to the surrounding landscape results in significantly more precipitation, leading to one of the more striking scenes that you would have seen. The land resembles that of north-central Minnesota: A land of many lakes, endless trees, and good trapping.

FIGURE 1.
Picture taken one mile southwest of the Turtle Mountains looking northeast at the glacial ice thrusts. The ice-thrust-dominated region of the Turtle Mountains has fewer bodies of water and more uneven topography compared to the rest of the Turtle Mountains.

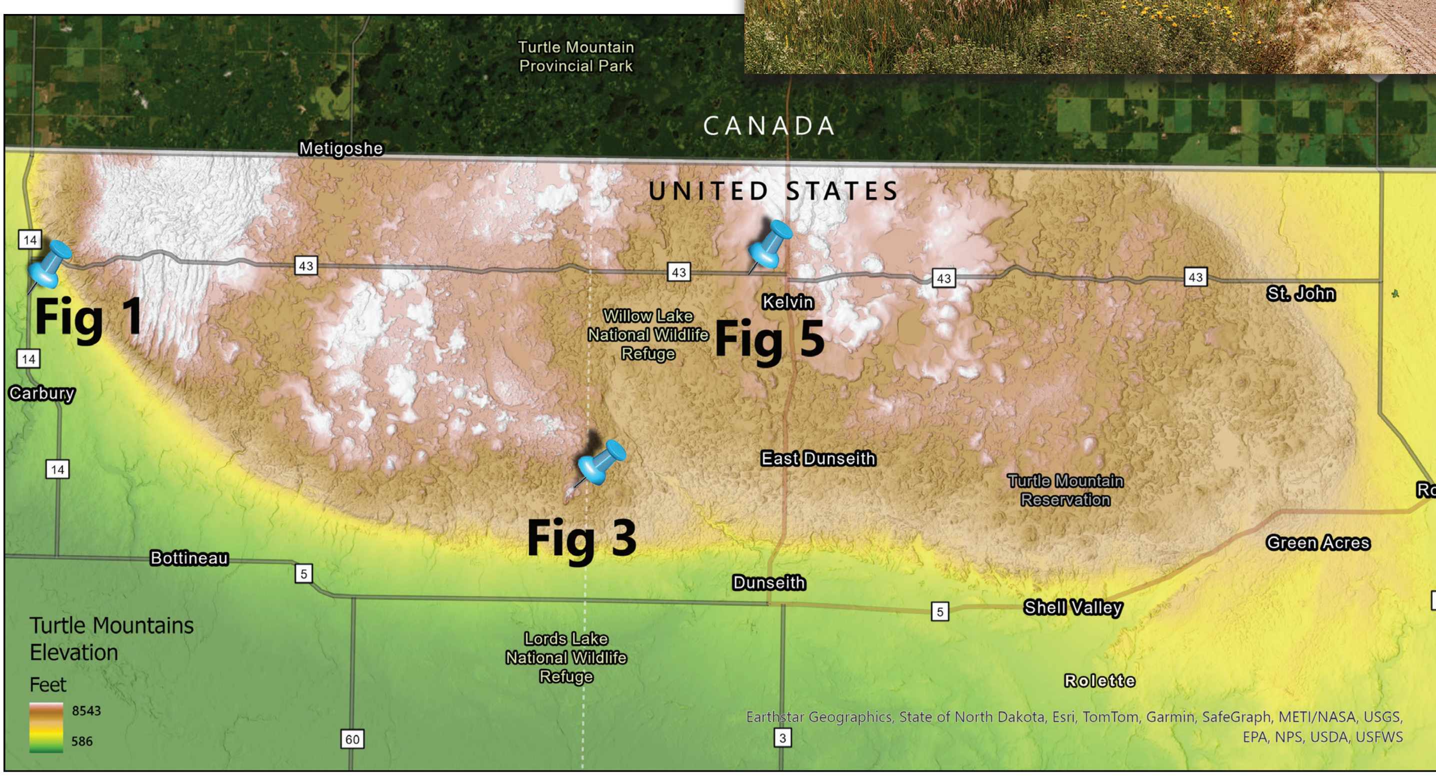

FIGURE 2.
One meter digital elevation model draped over multidirectional hillshade of the Turtle Mountains; with locations of photos taken.

If you were to look upon the Turtle Mountains 5 or 6 million years ago, you would not even recognize this part of North Dakota. Instead of hiking through dense trees and hundreds of small lakes and ponds, you would have been walking along a large plain crossed by rivers flowing northeast to Hudson Bay. As those rivers eroded the plain, they began to erode into the bedrock. Prior to the glaciation in the area, there was a period of erosion during the early Tertiary which could have removed the Paleocene Bullion Creek and Sentinel Butte Formations, along with exposing the Paleocene Cannonball and Cretaceous Hell Creek, Fox Hills, and Pierre Formations through river incision (Bluemle, 1985). The incised rivers went around a section of the plateau, leaving an "island" of Paleocene and Cretaceous bedrock. The topography near the end of the Pliocene, around 3 million years ago, was a flat landscape with a large 400- to 500-foot-high mesa right where our Turtle Mountains are today. Even before the advance of the earth-altering glaciers, a hint of our Turtle Mountains was beginning to form (Bluemle, 1985).

Now that the stage is set, here comes the driving mechanism that will shape what we see today. Early Pre-Wisconsian glaciers, though still going over the Turtle Mountains, followed the lowlands between the Turtle Mountains and the Missouri Coteau. At the start of the Late Wisconsinan glaciation, about 25,000 years ago, the glacial advance reached the Turtle Mountains and flowed over them for the last time. As the glacier advanced, the ice compressed while climbing over the 600 - 800 foot topographic high and sheared large volumes of rock and debris, incorporating it into the ice (Bluemle, 1986).

During the Late Wisconsinan glacial retreat, about 13,000 years ago, the glacial ice stagnated on the bedrock outlier of the Turtle Mountains. The stagnated glacial ice melted slowly and additional smaller glacial readvances went around the Turtle Mountains instead of over. While the ice on top was mostly undisturbed by the Souris and Leeds glacial lobes that surrounded the ice-covered mesa, the glacial lobes still produced significant high-relief ice thrusts along the western side of the Turtle Mountains (fig. 2) (Bluemle, 1985).

Disintegration ridges are another high-relief feature in the area. These ridges, which can be in many shapes including circular, form from sediment sliding into depressions on the ice (Bluemle, 1985). One of the most prominent disintegration ridges is Butte Saint Paul in the Butte Saint Pual State Recreation Area. If you were to have climbed this butte in the 1800s, you would have seen the iconic Turtle Mountain mix of water and trees, not much different from what we see today (minus some agricultural practice) (fig. 3).

With the final receding of the Late Wisonsinan glacier, the ice over the Turtle Mountains stagnated and began to melt without any interference from advancing and retreating ice. This stagnated ice had incorporated large volumes of rock and sediment, and as the ice melted, the debris formed an insulating layer on top, further slowing the rate of melting (Bluemle, 1986). While the Turtle Mountains were still ice-covered, lakes formed on the sediment-covered glacier and were filled with water derived from rainfall (more than 50 inches a year (Bluemle, 1986)). Lakes became inhabited with plants and animals, sustaining a functional ecosystem while depositing a thick layer of lake sediment over thousands of years on top of the ice (Deal, 1971). The ice melted for 3,000 years, and the Turtle Mountains were not ice free until 10,000 years ago (Deal, 1971); a dead-ice moraine, made of 100 to 300 feet of glacial sediment, now covers all the bedrock in the Turtle Mountains.

After the ice melted, the thick layer of lake sediment formed smooth elevated topography called perched lake plains which are easily identified using LiDAR (fig. 4). The chaotic topography of collapsed glacial till and ice-thrusts, and the smooth lake plains are the main topographic features that affect life in the Turtle Mountains today.

The Turtle Mountains look nothing like they did before the glaciers and the same can be said for most of North Dakota. The stagnant ice, which resulted in a dead-ice moraine, produced an inverted topography, where thinner layers of till, usually on thicker ice, became topographic lows, and areas of thin ice and thick till became topographic highs. Topographic lows which formed as the ice melted were

FIGURE 3.
Picture taken from the top of Butte Saint Paul (Butte Saint Paul State Recreation Area) looking west. The butte is a large disintegration ridge and is one of the tallest features in the southern part of the Turtle Mountains.

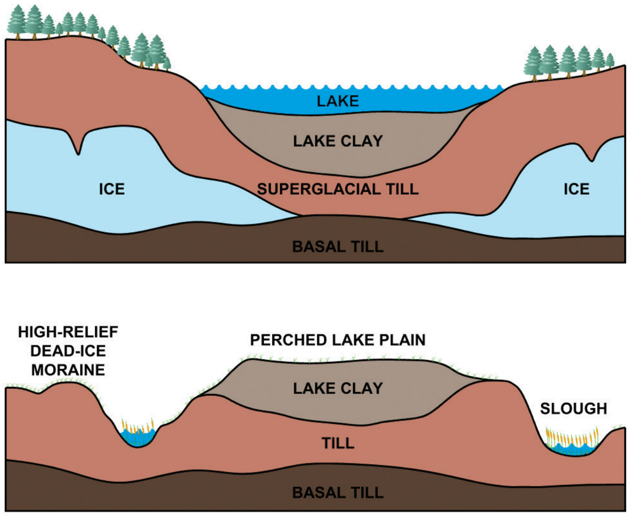

FIGURE 4.
Example of an elevated lake plane and its formation on top of the glacial ice. What used to be a water filled depression in the ice became a clay-rich perched lake plain once the ice melted.

primarily filled in with local rainfall runoff. About 8,500 to 4,500 years ago there was an arid period where the tree population was greatly reduced and most of the lakes either dried up or developed into sloughs. Those conditions lasted until approximately 4,000 years ago when the climate began to shift to resemble present day (Deal, 1971).

Collapsed till sometimes has relief up to 100 feet and slope angles of 7 degrees, normally along some ice-thrusts and shores of lakes, while the elevated lake plains are generally flat. Clay-dominant elevated lake-bottom soil became rich agricultural areas for alfalfa and hay (Bluemle, 1985) (fig. 5). While early settlers knew which areas might be good for farming and which for hunting and fishing, little did they know that geology going back millions of years directly influenced their daily lives. If you, as our young 1800s fur trader, were to walk the Turtle Mountains in 2025 you would recognize a few landmarks, some hills and certain lakes, but sparse would be the normal fur animals of your trade: beavers, muskrats, and martens. Instead, you would find lakes lined with homes and filled with water sports and large-scale agriculture. These differences that you observe wouldn't have been possible without the unique geology of the Turtle Mountains.

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FIGURE 5.
Picture taken looking northwest across a perched lake plain, locally known as Little Prairie, situated in the center of the Turtle Mountains. The flat topography and clay-rich soil created pockets of fertile soil within all the trees and lakes.

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SURFACE GEOLOGY 24K MAPS

Anderson, F.J., 2025, Surface Geology of the Leonard Quadrangle, North Dakota, North Dakota Geological Survey, 24K Map Series No. Lnrd – sg.

OUTSIDE PUBLICATIONS

Matheson, E.J., Cocker, M.D., Snyder, M.E., Funk, C., Boehner, R., Yang, C., Nicolas, M.P.B., and Kruger, N.W., 2025. The geology of Canadian potash: a critical mineral for feeding the world. FACETS. Vol. 10: 1-40. https://doi.org/10.1139/facets-2024-0363.

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