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FEATURES

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ON THE COVER:
Survey geologist Levi Moxness, lower right, excavates a small pit into the Cretaceous-Paleogene Boundary at Mud Buttes in southwestern Bowman County. Levi was obtaining rock samples for the Geological Survey's critical mineral project (Rept. of Investigation No. 130, p. 24). The rocks below Levi's feet are in the Hell Creek Formation and the rocks above are in the Ludlow Formation. The drone photograph was taken looking east.

Iceberg on Lake Superior
(Tim Trombley, Great Lakes Photography)

ICEBERGS IN NORTH DAKOTA

AND THE CURIOUS ICE-DRAG MARKINGS OF GLACIAL LAKE AGASSIZ

BY FRED J. ANDERSON

INTRODUCTION

How do we know that there was an extensive glacial lake in North Dakota that covered most of the Province of Manitoba along with parts of Saskatchewan and Ontario and extended as far south as eastern North Dakota and northwestern Minnesota (fig. 1)? There are hundreds of feet of glaciolacustrine sediments right beneath our feet in the shallow subsurface of the Red River Valley, and there are numerous former beaches, lakeshores, deltas, and drainage features identified by geologists over the years (Holland, 1957). There are also several microrelief geomorphic features, like ice-drag marks (fig. 2), left behind in the glacial lake sediments from the bottom (sometimes called the keel) of icebergs dragging across the shallow lake bottom (fig. 3). These features were recognized and described by North Dakota Geological Survey geologists over 50 years ago (Clayton and others, 1965).

Ice-drag marks have been mapped in North Dakota within the offshore lake sediments in five of the nine counties in the Red River Valley and include: Pembina, Walsh, Grand Forks, Traill, and Cass. No ice-drag marks have been mapped in Richland County (fig. 2), in the southeast corner of the North Dakota portion of the Red River Valley.

FIGURE 1.
Glacial Lake Agassiz at its maximum extent flooded 110,000 square miles mostly in Canada, extending to the west into Saskatchewan and south into North and South Dakota and Minnesota. Although the lake is understood to have never occupied this large expanse at any single time, its existence and great expanse can be deduced, as geologists do, from the landforms and sediments left behind.

These features are revealed in detail when coupling aerial imagery (fig. 4) and contemporary (Maike, 2016) LiDAR elevation data (fig. 5). It is conceivable that this dense scratchwork pattern records ice breakup behind the lake during the last recession of glacial ice around 9,000 years ago (Arndt, 1977).

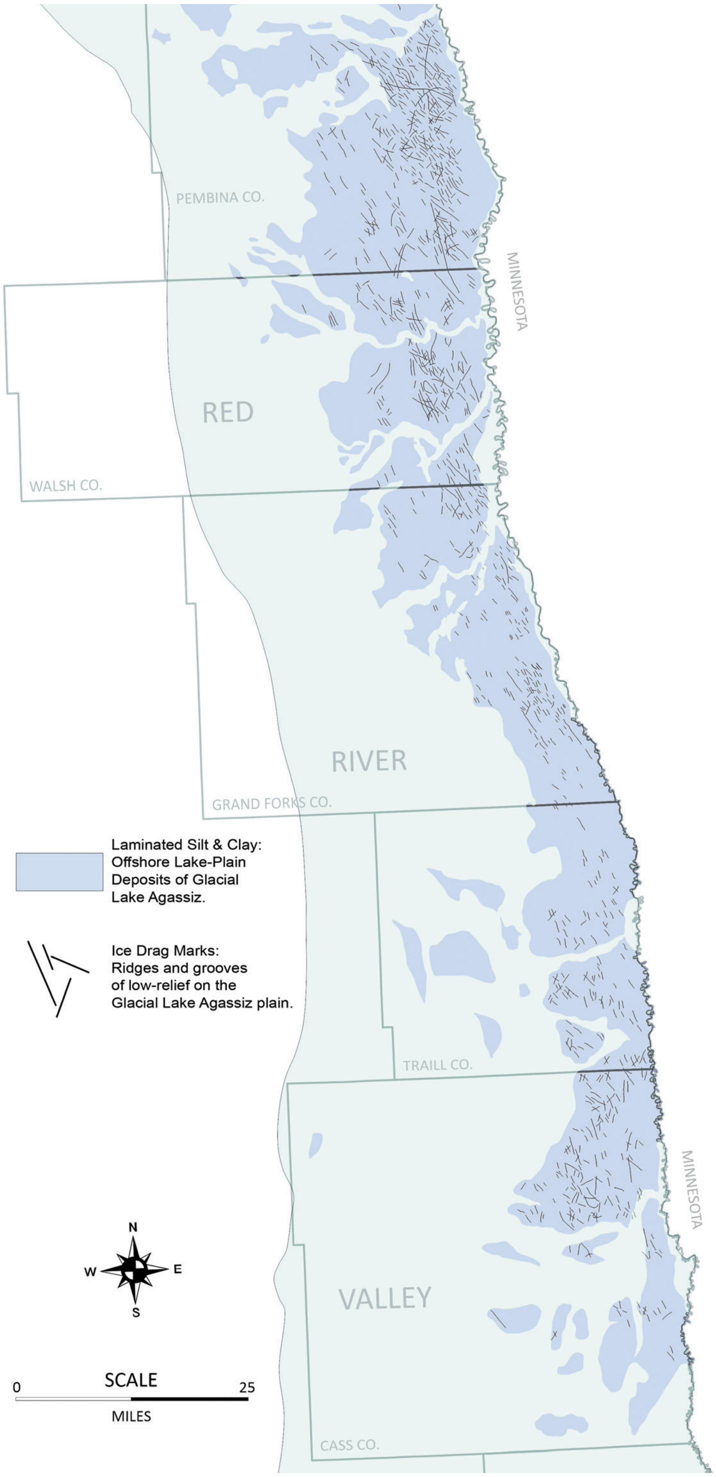

FIGURE 2.
Ice-drag markings mapped in North Dakota (from Clayton and others, 1980). There are no ice-drag marks mapped in Richland County, presumably due to the relatively small amount of soft glacial lake offshore sediments present which are required to preserve these types of features. Southeastern and northeastern directional trends are observed consistently in these features.

A fundamental concept in geology is the principle of Uniformitarionism, or in more simple terms "the present is the key to the past." With this concept in mind, geologists look for modern comparisons or analogs to help explain physical features and landforms that we find throughout the geological record. An example that compares quite well to our Lake Agassiz ice markings is revealed in recently published seafloor mapping studies from offshore

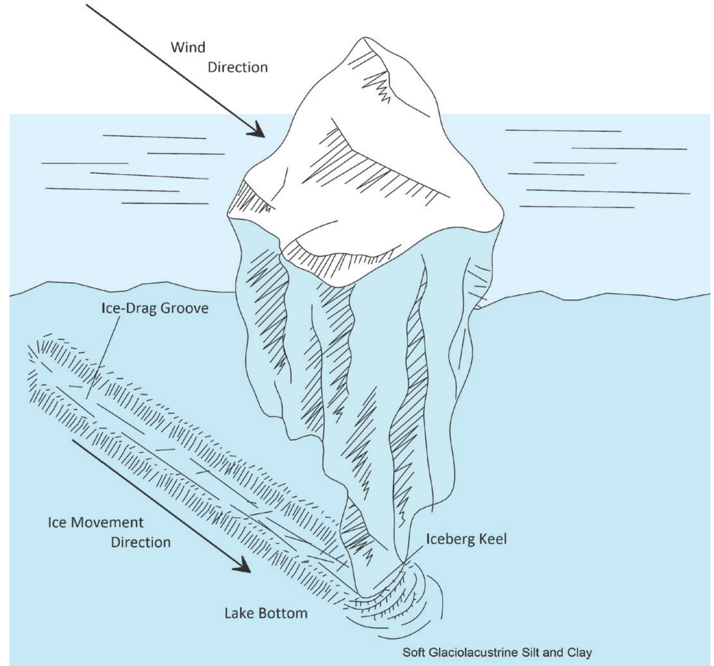

FIGURE 3.
Suggested mechanism of ice-drag mark formation on the bottom of Glacial Lake Agassiz. As the wind pushes the iceberg along in the water the keel of the submerged portion of the iceberg in contact with the soft lake bottom sediments cuts its own groove along a path that reveals past wind directions on the lake.

FIGURE 4.
Ice-drag marks shown in digital aerial imagery from northeastern Pembina County in northeastern North Dakota are a striking feature as seen by air. On the ground these features are virtually indistinguishable to the casual observer.

Svalbard, a Norwegian island archipelago in the Arctic Ocean (Dowdeswell and others, 2016) where similar looking iceberg-drag marks are found on the modern seafloor (fig. 6).

CHARACTERISTICS OF LAKE AGASSIZ ICE-DRAG MARKINGS

In the Red River Valley, our interesting ice-drag markings can stretch for tens of miles and tend to trend in northwest to southeast orientations along with intersecting marks in southwest to northeast orientations. There are also a few curvilinear features which trend from the south and then loop back to the north suggesting changing weather patterns and wind directions on the lake (Clayton and others, 1965). Using the principle of cross-cutting relationships, several of these marks show relative age differences between the ice-drag markings. However, the cross cutting does not appear to follow any specific directional relationships as many of the southwest trending ridges and grooves are crosscut or appear contemporaneous with southeast trending features, and vice-versa (fig. 7).

Most of the ice-drag markings appear to surround some of the areas that show wave-modified bedforms, suggesting that these ice-drag markings occurred later, presumably as the lake ice was entering the open water during glacial recession along the ice-margin. Some of the ice-drag features cross-cut one another which provide clues as to relative ages between different features although some appear to have occurred at roughly the same time.

These subtle microrelief features are on the order of just a few feet in local relief (fig. 8) and are nearly indistinguishable from a ground-based observer's perspective.

A statistical analysis of the lengths of 976 mapped ice-drag features indicates that these features range from 0.36 to 16.04 miles in length with a mean of 1.55 miles.

FIGURE 5.
National Agricultural Imagery Program (NAIP) aerial imagery overlain on LiDAR surface model displays linear ice-drag marks in the left section of land with the sinuous wave-modified bedforms in the adjacent section. The northwest to southeast orientation of the ice-drag markings suggests similar wind directions. The wave-modified bedforms in the section of land at right suggest offshore wave activity perpendicular to the emplacement of Lake Agassiz beaches-oriented northwest to southeast.

Over 82% or 804 of these marks are less than two miles in length (fig. 9). The distribution of the measurements of these trends is log-normal which is a numerical characteristic of the measurement of natural geologic features (Koch and Link, 1980), which further supports that these are indeed natural and not artificially interpreted features. A directional

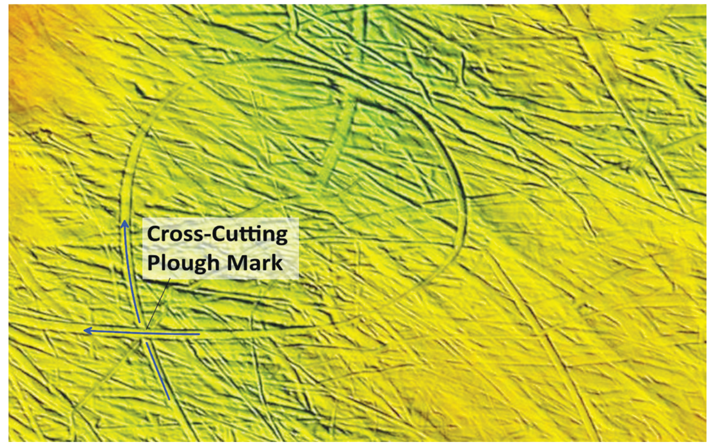

FIGURE 6.
Markings on the seafloor of the Arctic Ocean near Svalbard, Norway. These features, called iceberg plough marks, exhibit remarkably similar groove and ridge patterns to Lake Agassiz ice-drag markings. Using the geologic principle of cross-cutting relationships, we can see that one of these icebergs had traveled in one direction (towards the top of the image) first, and then turned around in a big circle reversing its path and finally moved off in another direction (towards the left of the image) cutting across its previous track.

FIGURE 7.
LiDAR elevation map with draped NAIP imagery from 2016 showing intersecting ice-drag marks in Pembina County, North Dakota. Several older north-south trending ice grooves at this location are cut through by a younger east-west trending singular groove suggesting a possible change in lake ice conditions.

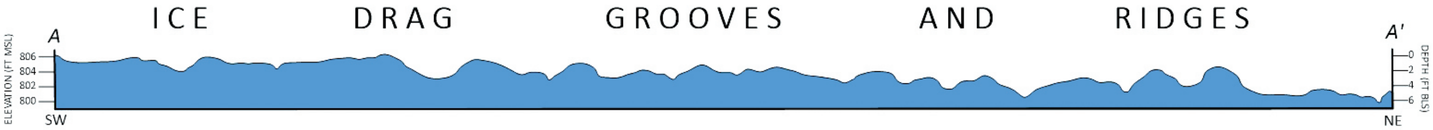

FIGURE 8. Topographic section A to A′ from LiDAR surface model of the ice-drag features noted in Figure 5. Local relief on these grooves and ridges is only a few feet. This profile has been considerably stretched or exaggerated in the vertical scale to visualize these micro-relief features as the horizontal distance depicted here is over a mile.

analysis of 976 ice-drag markings as mapped by Clayton and others (1980) reveals two dominant trends (fig. 10). A large primary (1º) trend-oriented northwest to southeast (S 44º E) and a much smaller secondary (2º) trend-oriented southwest to northeast (N 36º E).

DISCUSSION

Using a southward notation for the primary directional trend assumes that ice-movement directions would have been towards the south-southeast, away from the main ice body to the north in the direction of prevailing winds, which are assumed to be from the northwest to the southeast. The smaller secondary directional trend towards the northeast may be the result of changing wind patterns from a more southward direction. The relationship of these two groups suggests two or more dominant ice breakup events occuring on the lake just prior to the final lake recession.

More in-depth studies of these fascinating micro-relief structures are now possible with the increased availability of LiDAR maps and data products, and may help to reveal several new insights into the history of this expansive glacial landscape.

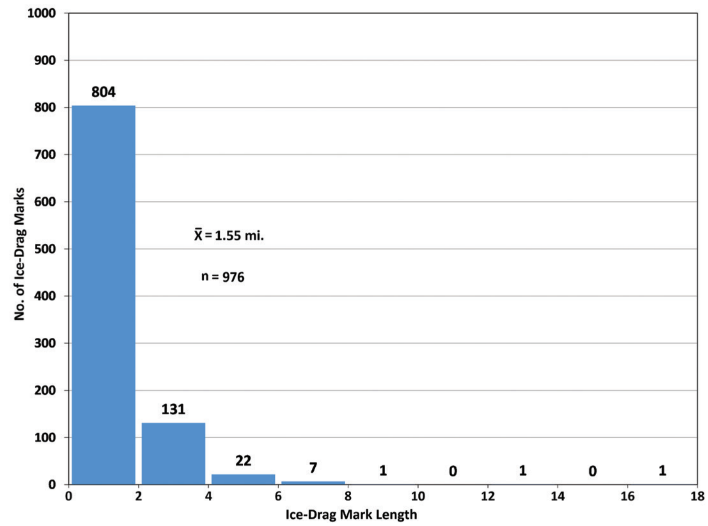

FIGURE 9.
Distribution of ice-drag mark lengths mapped in offshore sediments of the former Glacial Lake Agassiz in North Dakota. Most of these linear features are less than two miles in length and follow a lognormal distribution which is a numerical characteristic of the measurement of natural features.

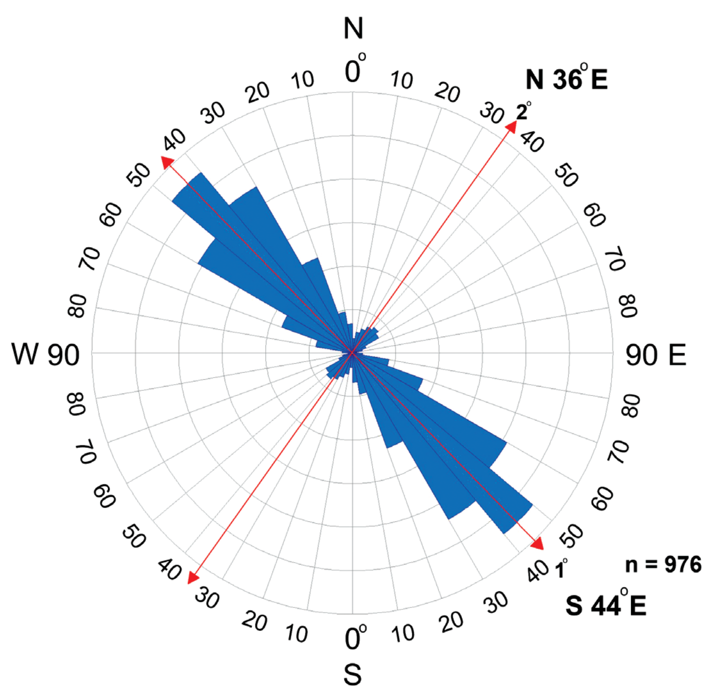

FIGURE 10.
Frequency rose diagram of the orientations of 976 mapped ice-drag features on the Glacial Lake Agassiz plain. A dominant southeastern trend and smaller northeasterly trend are revealed in this data.

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INDENTIFYING ACTIVE LANDSLIDES

REPEAT LiDAR COVERAGES ALLOW REMOTE SENSING OF SLOPE MOVEMENT

BY CHRISTOPHER MAIKE AND LEVI MOXNESS

LANDSLIDE IDENTIFICATION: PAST, PRESENT, AND FUTURE

Before any building foundation or road base is constructed on any grade, before any fiber optic, electric, oil, gas, water, or sewer line can be laid, engineers must first consider slope stability. Despite its reputation as a relatively flat plains state, even North Dakota's more gentle slopes are often comprised of weak, clay-rich sediments that cause costly impacts to infrastructure where they fail. The North Dakota Geological Survey (NDGS) documents the settings in which these slope failures have occurred across the state through its landslide mapping program. Recent Geo News articles have documented the progress of the program, including the dramatic advances in landslide identification via LiDAR (Light Detection and Ranging) and digital aerial photography over the nearly 20 years NDGS geologists have been mapping them (Murphy, 2017; Moxness, 2019; 2022). To date, the NDGS maintains an inventory of over 45,000 slope failures within North Dakota, a number that will continue to grow as older maps are updated using the latest digital imagery.

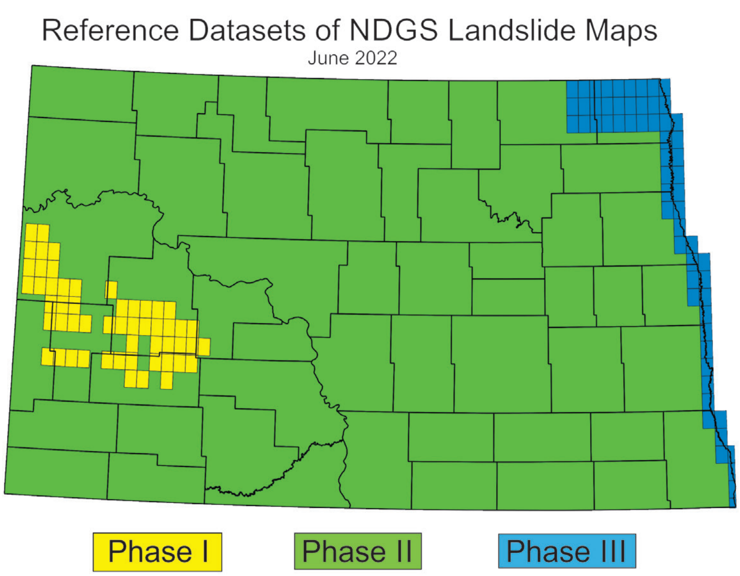

FIGURE 1.
NDGS landslide maps available as of June 2022 based on the reference dataset used. Phase I: 1950's and 60's black-and-white aerial photographs viewed in stereopairs and early digital imagery, Phase II: historical aerial photographs, modern NAIP digital aerial imagery, and LiDAR hillshade models: Phase III: the existing landslide maps, supplemented with 2021 aerial imagery and differential elevation models produced from a second LiDAR collect.

The NDGS maps landslides at 1:24,000 scale in standard 7.5-minute quadrangles (an area just under 6 by 9 miles). Shapefiles or maps (landslide areas plotted on a USGS topographic base) for all 1,464 North Dakota quadrangles can be downloaded at https://www.dmr.nd.gov/ndgs/landslides/. These maps utilized the best reference imagery available at the time they were completed, and as a result newer maps are more comprehensive than older maps. Internally, the NDGS marks "phases" of the program based on the reference dataset(s) used (fig. 1). About 300 maps were published under the first phase of landslide mapping between 2003 and 2017, where landslide delineation was primarily done via stereo projection of black-and-white 1:20,000-scale aerial photographs from the 1950s and '60s. The resolution of digital aerial and satellite imagery increased several-fold during this period and played a more prominent role as a reference in later phase I maps. Phase II work began as LiDAR coverage became available over western North Dakota (where most early mapping was occurring) in 2017. The bare earth hillshade models produced from LiDAR imagery allow for terrain visualization without vegetation, which led to a significant increase in the number of landslides identified (Moxness, 2019; 2022; Maike, 2021). By 2021, the rest of the state was mapped using phase II methods (fig. 2) and most of the phase I maps have since been updated.

Inventory maps do not attempt to characterize landslide susceptibility directly; rather, by documenting where slopes have failed, these areas and those nearby (similar in slope angle or geologic unit) can be avoided or more rigorously geotechnically assessed. That said, it is apparent that many mapped landslide areas are currently active (and thus pose a high risk to nearby infrastructure), while many others are relatively stable (lower risk). Visually identifying slope movement after landslide "events" is easy, especially when 4,790 cubic yards of material is deposited directly onto a busy roadway on a Sunday afternoon (Moxness, 2020), but it is the slower moving, seemingly stable slopes that cause most of the damage because they are not avoided. We know that many of the massive rotational slumps across the state likely occurred at the end of the last ice age (over 10,000 years ago). Ice sheets diverted massive amounts of water across the landscape, which cut steep slopes through weak bedrock from the Little Missouri Badlands to the Sheyenne Valley to the Pembina Gorge. The conditions which caused these slumps to form have long passed. Did most of the displacement in these bedrock masses occur in a short time at the end of the ice age, or have they continued to incrementally slip downhill for millennia? The reality may be somewhere in between, but either way the answer cannot be observed by visually comparing photographs of differing resolutions across a few decades. High accuracy elevation data across multi-year timescales is needed to recognize more subtle movement on slopes, and the latest repeat LiDAR data from eastern North Dakota allows us to begin the next phase of landslide mapping.

FIGURE 2.
Phase II landslide mapping along the Sheyenne River Valley using 1:20,000-scale 1959 aerial photographs viewed through a stereoscope (bottom), a Barnes County surface geology map (left screen), LiDAR DEM (center screen), and aerial imagery on Google Earth (right screen).

LiDAR AND ITS NEW COVERAGES IN NORTH DAKOTA

LiDAR is a remote sensing technology utilized in many STEM fields. It has a wide range of applications from cell phone cameras to autonomous car technology, but in natural resource fields it is most commonly used for terrain modeling (Maike, 2016). Geologists utilize this detailed model in landslide identification, surface geologic mapping, paleontology surveying, flood mapping, and erosion modeling (Maike, 2021). For terrain modeling, LiDAR is collected over large areas and used to create a three-dimensional image of Earth's surface. To briefly explain this technology, a plane carrying high-precision GPS equipment flies at low altitude, and light waves from the LiDAR are emitted to the surface and travel back to the sensor (fig. 3). The time it takes the light to travel is known as the two-way travel time. From this, a precise X,Y,Z (latitude, longitude, elevation) grid of millions of points is acquired for a dataset. This type of grid is known as a three-dimensional point cloud, represented as a .LAS file. For North Dakota, on average, the point clouds

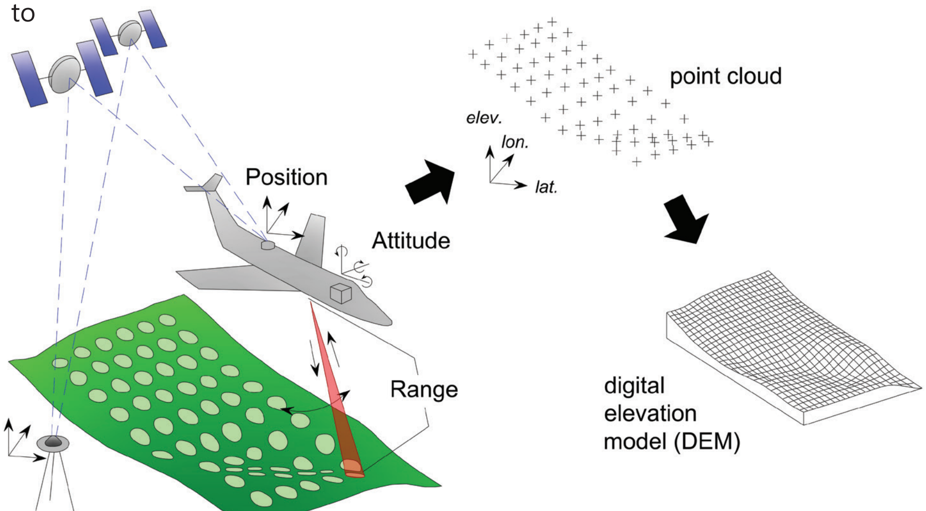

FIGURE 3.
A General representation of airborne LiDAR being acquired and processed. Adapted from https://historicmappingcongress.files.wordpress.com/2012/06/lidar.jpg (Date retrieved July 7, 2016).

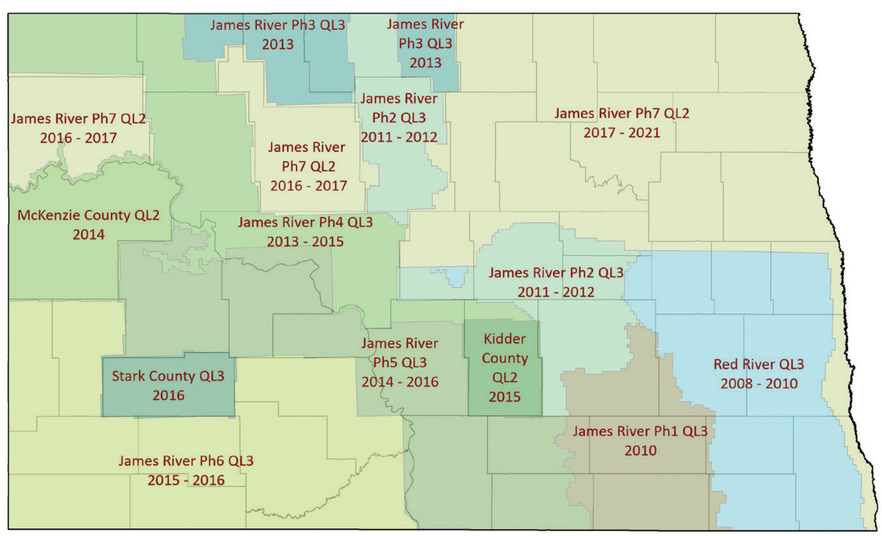

FIGURE 4.
The locations, dates, and quality levels of LiDAR within the State of North Dakota. This data is managed by the North Dakota Department of Water Resources.

typically have an average horizontal spacing of approximately one meter between points. From this dense array of points the elevation between them can be interpolated as pixels, resulting in a model of Earth's surface known as a DEM (Digital Elevation Model). Software can filter out trees, vegetation, buildings, etc, which results in a smooth "bare-earth" model.

The primary sources of funding to collect the LiDAR data within the state of North Dakota (fig. 4) are at the Federal, State and County Level, such as: US Fish and Wildlife Service, Natural Resources Conservation Service, Federal Emergency Management Agency, US Army Corps of Engineers, North Dakota Department of Water Resources, McKenzie County, and the International Water Institute. The stewardship of this

TABLE 1.
The different levels of LiDAR quality and associated metrics. Adapted from https://www.usgs.gov/3d-elevation-program/topographic-data-quality-levels-qls (Date retrieved May 26, 2022).

QUALITY LEVEL	DATA SOURCE	VERTICAL ACCURACY RMSEz (cm)	NOMINAL PULSE SPACING (NPS) meters	NOMINAL PULSE SPACING (NPD) points per square meter	DIGITAL ELEVATION MODEL (DEM) cell size (meters)
QL0	**Lidar**	**5 cm**	**<= 0.35 m**	**>= 8 pts/square meter**	**0.5 m**
QL1	**Lidar**	**10 cm**	**<= 0.35 m**	**>= 8 pts/square meter**	**0.5 m**
QL2	**Lidar**	**10 cm**	**<= 0.71 m**	**>= 2 pts/square meter**	**1 m**
QL3	Lidar	20 cm	<= 0.35 m	>= 0.5 pts/square meter	2m
QL4	Imagery	139 cm	N/A	N/A	5 m
QL5	IfSAR	185 cm	N/A	N/A	5 m

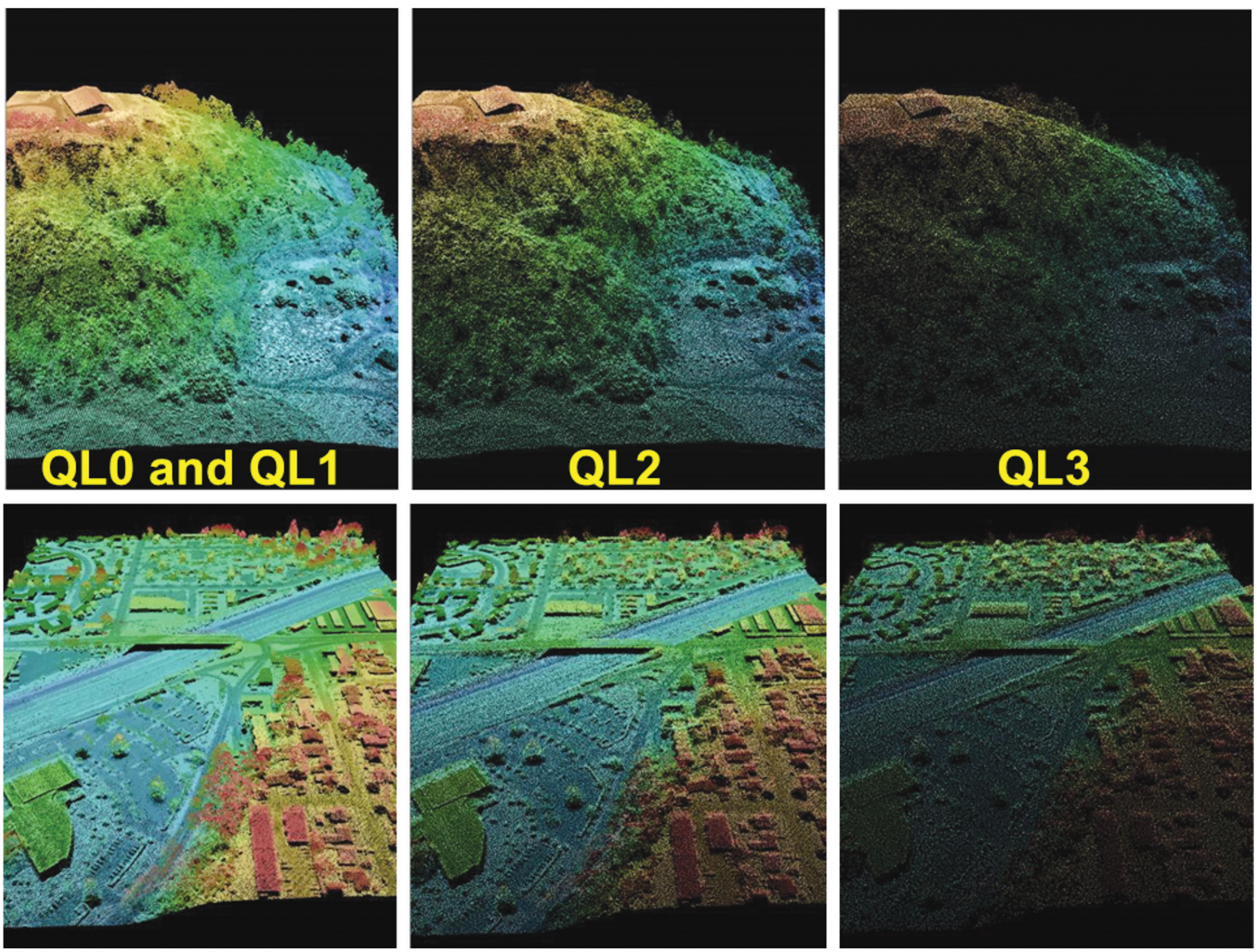

FIGURE 5.
A visual representation of LiDAR point cloud quality levels. This gives insight into how a more dense point cloud results in a higher quality image. https://www.usgs.gov/media/images/figure-1-3d-view-lidar-point-clouds-demonstrating-qls (Date retrieved May 26, 2022).

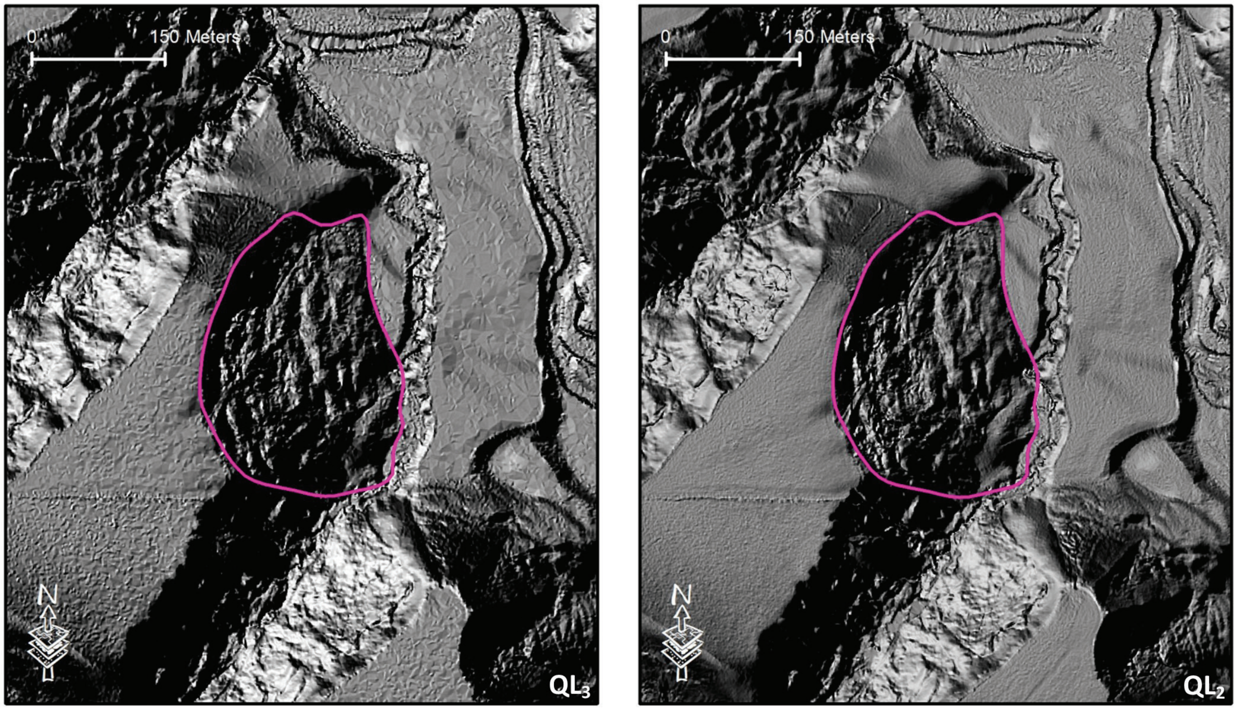

FIGURE 6. A landslide (outlined in pink) overlain on QL3 (left) and QL2 (right) hillshades in the Pembina Gorge. The QL3 data was collected in the 2008/2009 time frame and the QL2 data was collected in 2018.

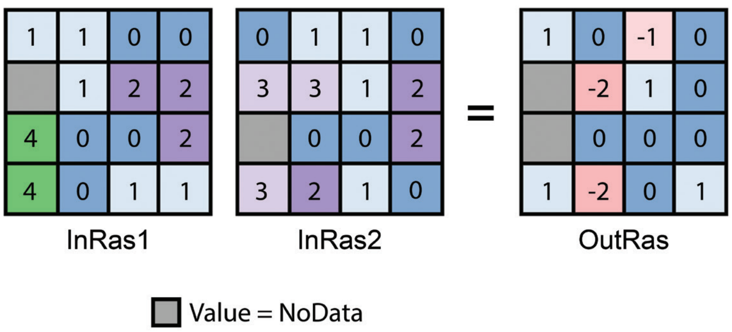

FIGURE 7.
The graphic represents the second raster being subtracted from the first raster. This process allows elevation change to be detected. https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/minus.htm (Date retrieved June 1, 2022).

data is handled by the North Dakota Departments of Water Resources and can be found at (https://lidar.swc.nd.gov). The Department of Water Resources has organized tiles through the state where data can be downloaded such as: ASCII grids, DEM images, Intensity Hybrid images, and .LAS files. The NDGS found that it would be downloading and using the entirety of the data for its use in landslide mapping, surface mapping, and other functions at 1:24,000 and 1:100,000, the scales commonly used in standard quadrangle maps. The NDGS provides these 1:24,000 and 1:100,000 maps as PDFs, DEMs, and hillshades available at www.dmr.nd.gov/ndgs/lidar/.

There are different quality levels used to determine the grade of LiDAR data, as defined by the USGS 3D Elevation Program (3DEP). The State of North Dakota in its entirety has had LiDAR collected at QL3 quality level (fig. 4). Some 10 years after the first QL3 was collected, QL2 data has now been collected, primarily in NE North Dakota, the Red River corridor, and

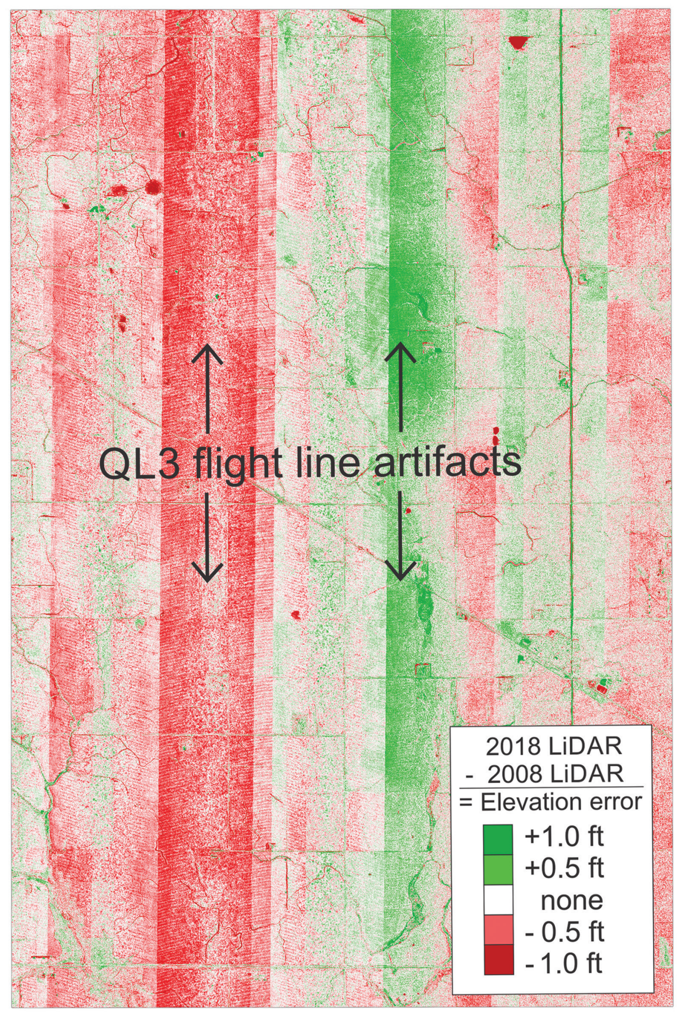

FIGURE 8.
Raw differential elevation raster of the Osnabrock quadrangle, a flat, stable area, illustrating the different vertical precision between 2008 QL3 LiDAR and 2018 QL2 LiDAR. Artifacts from the older flight lines are visible but are typically within +/- 1 foot.

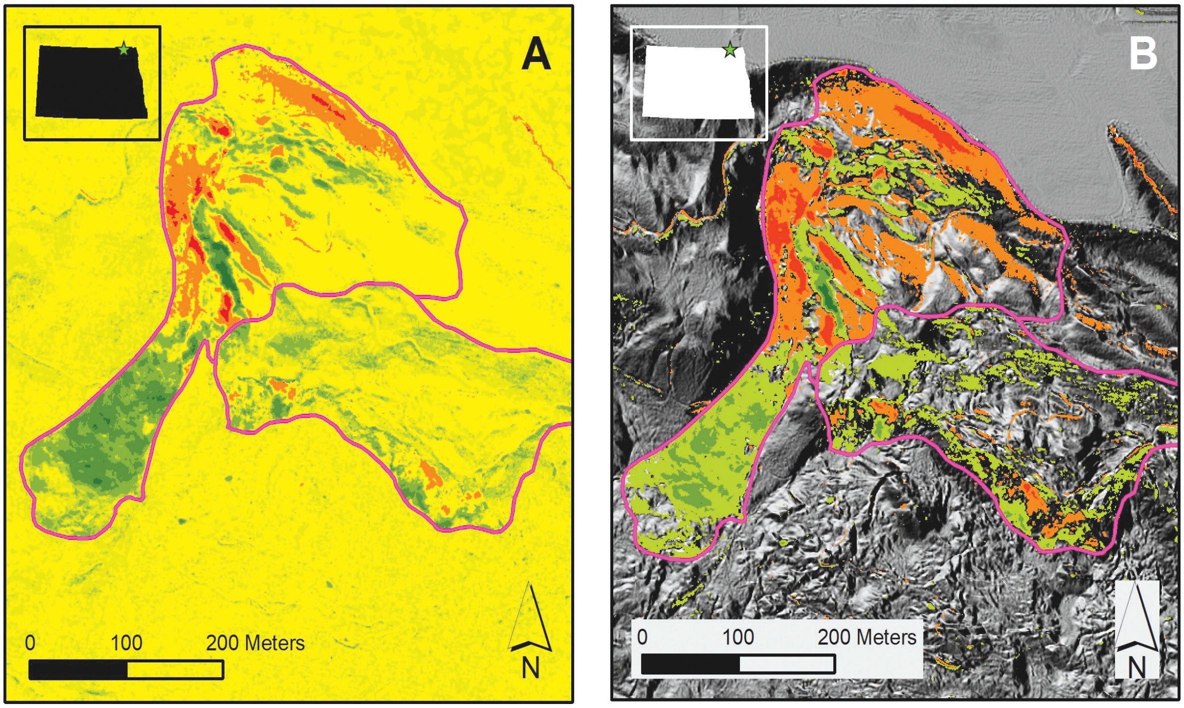

FIGURE 9.
(A) on the left displays two landslides (identified by pink polygons) located in the Pembina Gorge region of North Dakota. (A) shows the result of how the difference calculation appears unfiltered. The yellow color is interpreted to be "noise." (B) on the right displays how the difference calculation is presented after the noise is filtered out from the data. This data is then overlain on 2018 QL2 LIDAR data. In both maps (A) and (B) shades of red/orange are negative z-values (collapse), whereas, green areas are positive z-values (deposition/accretion).

McKenzie County. The different characteristics of quality levels are displayed in Table 1 and visually from the USGS in Figure 5. A large portion of the rest of the State of North Dakota is scheduled to have LiDAR QL2 available in the coming years. QL3 data, although "lower" quality, was a massive step from older elevation datasets and greatly expedited the NDGS landslide mapping program.

The addition of a QL2 dataset has provided a slight increase in quality, allowing imagery to become a bit more refined. Figure 6 displays a comparison of a landslide overlain on a hillshade model produced from QL2 and QL3 data. This landslide is located in the heavily collapsed shale bedrock of the Pembina Gorge. The comparison of the two quality levels shows that while QL2 data has a denser point cloud, resulting in a smoother DEM, QL3 hillshades are very comparable when viewed at the scale used by the NDGS landslide mapping program (1:24,000). For slope investigations at this scale, the primary advantage of the new LiDAR is not its higher quality but its existence as a second comparative dataset.

PHASE III LANDSLIDE MAPPING

The availability of two LiDAR datasets, collected years apart, gives insight into land displacement that occurred during this window of time. The Minus tool (Spatial

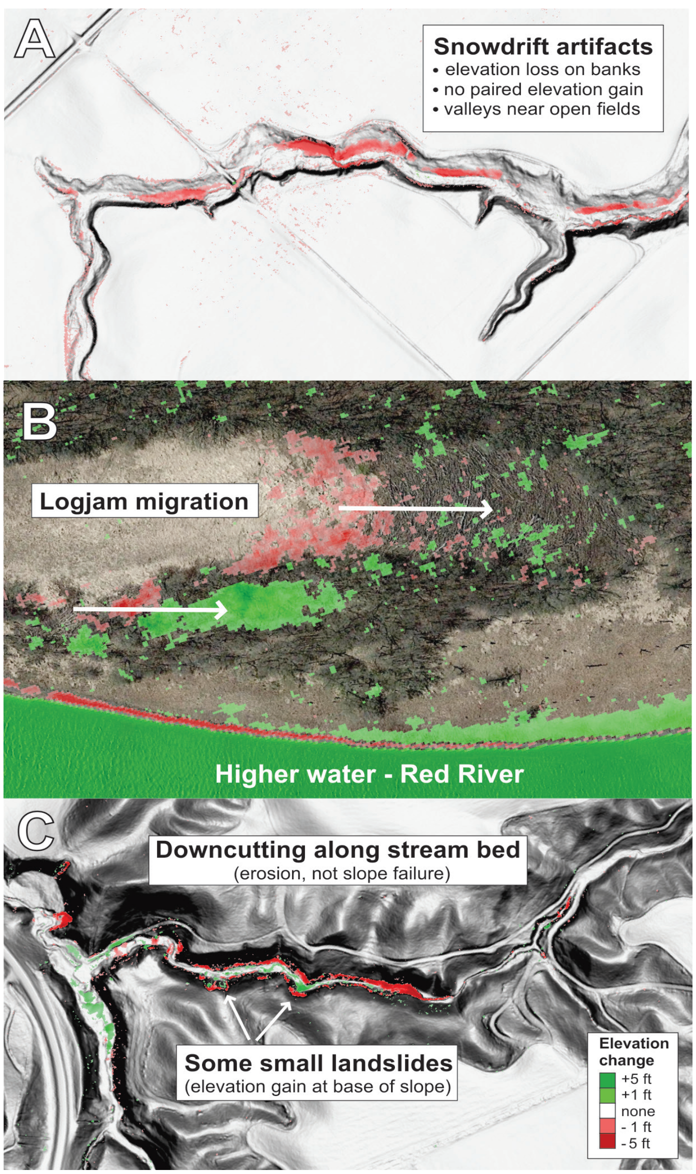

FIGURE 10.
Elevation changes that could be confused for landslides. (A) Snowdrifts may be captured by LiDAR flown early in the season, typically along the north or west wall of draws near open fields. (B) Dense logjams along the Red River south of Pembina are not filtered out on bare-earth LiDAR, and show downstream movement from seasonal flooding. (C) Fluvial incision from downcutting streams near the heads of draws.

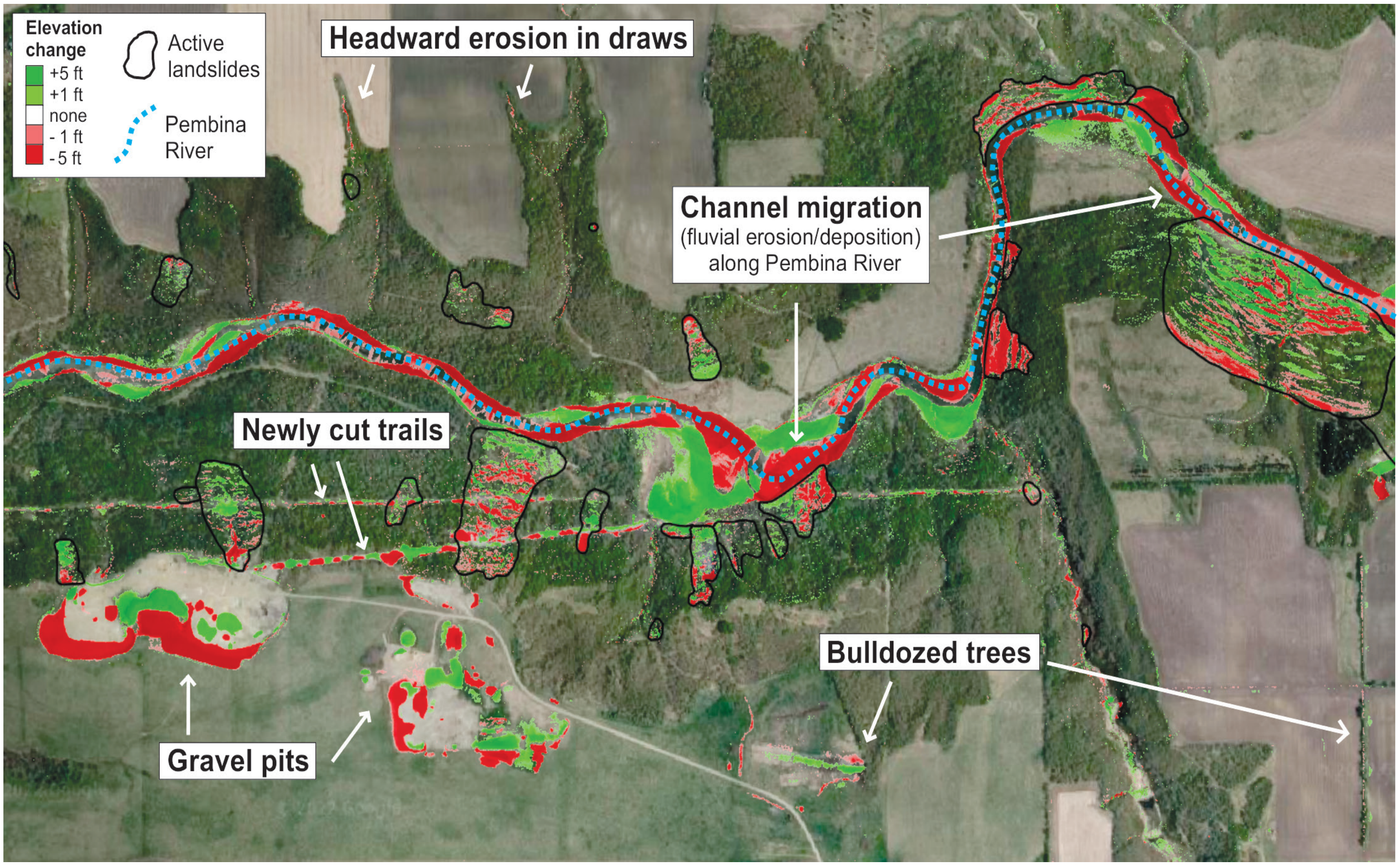

FIGURE 11.
Differential elevation raster overlaid on aerial imagery of the Pembina River southwest of Walhalla, ND. Elevation changes (between 2008 and 2018) caused by landslides and many other sources are apparent.

Analyst) in ArcGIS, allows for the difference between two elevation rasters to be calculated, resulting in an output of X (latitude), Y (longitude), and Z (vertical displacement) (fig. 7). All geospatial data has some amount of error, however, and there is a degree of noise in the resulting differential elevation raster. Nearly all of this "disagreement" between the two datasets is within one vertical foot (in the positive or negative direction), which is mostly artifacts between flight lines within the older, lower quality LiDAR dataset (fig. 8). There is also the aforementioned normal imprecision during data acquisition and post-processing. Much of this noise can be removed. NDGS geologists filter out any displacement from -1 to +1 feet by increasing the transparency of this interval on the differential elevation raster when looking for landslide movement (fig. 9).

Once the noise is removed, the resulting dataset shows areas where the ground has moved up or down over one foot between the two LiDAR collects, which in eastern North Dakota is about 10 years. Geologists can overlay this raster on the phase II landslide dataset and identify which have been active or delineate lobes of movement within individual slides. Not all of the signal changes over one foot can be attributed to landslides, however. Geologists map while referencing multiple years of aerial photographs and hillshade models to avoid mapping non-landslide features common on slopes (fig. 10). Snowdrifts, logjams, ponding water, human earthwork, and stream erosion (which can undermine a slope but is not mapped in isolation) all produce changes that appear on the differential elevation raster, oftentimes in between or overprinting signal from actual landslides (fig. 11).

One of the first areas to receive a second LiDAR collect is also one of the most landslide prone: the Pembina Gorge in eastern Cavalier County. Phase II mapping in 2019 showed that nearly every slope in the gorge had failed, including everything from massive rotational slumps to highly fluidized earthflows. In the Vang quadrangle alone, 1,709 landslides were mapped, including 604 active areas between 2008 and 2018 (Maike and others, 2021). NDGS geologists take special note of landslide activity in close proximity to infrastructure, and thus were paying close attention when the integrity of dams in the area, more specifically, the Bourbanis Dam, was the subject of much regional media reporting on May 3, 2022. Given that virtually all slopes along the Pembina Escarpment and within the gorge have failed, some of these dams may have been built onto landslide material when they were constructed between 1955 and 1961, and active landslides had recently been mapped above the southwest end of Bourbanis Dam (fig. 12). As more information became

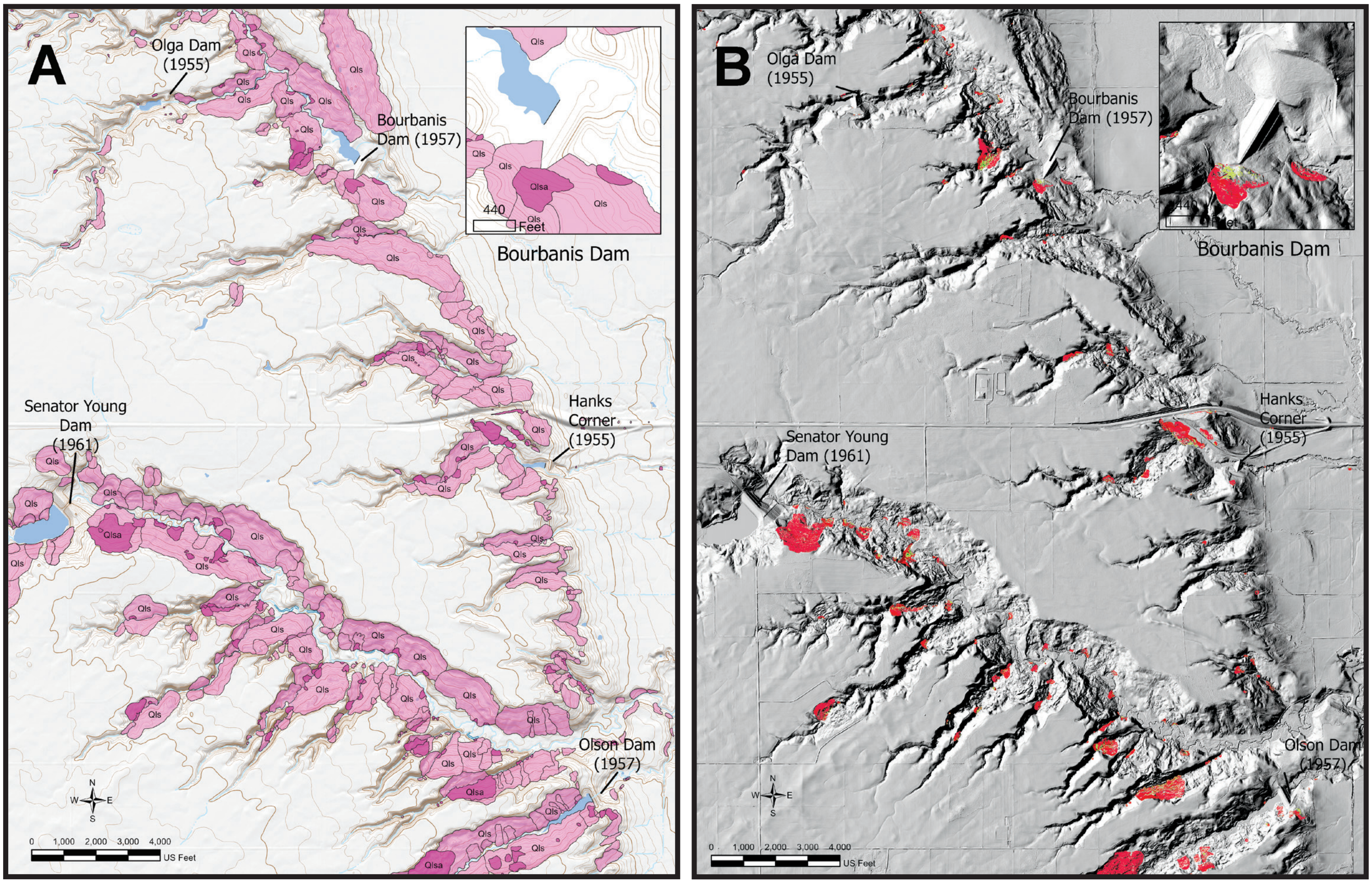

FIGURE 12.
Proximity of landslides to dams in northeast North Dakota. Located in the Pembina Gorge region, Map A (left) displays mapped landslide polygons (Qls-lighter pink) and active landslides (Qlsa-darker pink) overlain on a topographic shaded relief base layer. Qlsa are areas where movement occurred between 2008/2009 and 2018, shown on Map B (right) as areas of elevation loss (red) and elevation gain (green) are overlain on a QL2-quality hillshade.

available later that day, it became clear landslides posed no direct role or imminent threat in the emergency. Erosion from heavy spring precipitation threatened the integrity of the spillway. The National Guard delivered sandbags via UH-60 Black Hawk helicopters and prevented further downcutting. The dams in the Pembina Gorge are a good application for contextualizing landslide activity around important infrastructure with phase III landslide mapping. You wouldn't need a differential elevation raster to notice a catastrophic slope failure, but most impactful slides are the subtle shifts of vegetated slopes, quietly undermining anything constructed within their boundaries. Although current methods don't allow for the detection of the most subtle shifts (moving less than one foot vertically), the future may hold increasingly precise LiDAR coverages for North Dakota, which will in turn provide increasingly detailed data on landslide activity. The intersection of geology, lasers, and a window of few years' time has provided an entirely new dataset with which NDGS geologists can characterize the state's most hazardous slopes.

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A NEW UPCYCLE POTASH TREND EMERGES

BY NED W. KRUGER

INTRODUCTION

The NDGS has completed a map series depicting the thickness of Prairie Formation salt deposits and is continuing to produce maps depicting thicknesses of each of the six potash-containing members which are observed in North Dakota and log-based estimates of potassium oxide (K_2O) percent concentration for those members, from various wells (figs. 1 & 2). These maps are at the 1:100,000 scale and are expected to be useful for planning future potash exploration activities or potential dissolution of salt caverns to be used for storage.

As the southern extension of the salts mined for potash in Canada, the Prairie Formation potash deposits in North Dakota have huge potential for future production (Kruger, 2020). Due to the shape of the Williston Basin, the potash deposits are deeper in North Dakota than Saskatchewan and Manitoba, but account for most of the 7 billion tons of estimated potash resources within the United States.

PRODUCTION AND PRICES INCREASE

World potash production again reached new all-time highs in both 2020 and 2021 (estimated) following a decline in production in 2019 (fig. 3) (Jasinski, 2022). Worldwide, it is estimated that production was approximately 74% of total mine capacity (62.3 million tons) in 2021, and by the end of that year, forecast analysts projected production could near 69 million tons by 2025, mostly from new mine and expansion projects in Canada, Belarus, and Russia. The last phrase has raised some eyebrows.

Russia and Belarus are the second and third leading potash producers for world markets, respectively, and together account for approximately 35% of world potash production. Even prior to the Russian invasion into Ukraine, the Belarussian potash producer had already been placed under U.S. and other western governmental sanctions in 2021 in response to the Belarussian president's crackdown against political opponents. Additional sanctions on their exports and those of Russia may shake-up the markets further. Ukraine is a major exporter of fertilizers, wheat and other crops. Prices for Canadian potash more than doubled in March and now stand at its highest level since the rise and fall in prices experienced during the financial crisis of 2008 & 2009 (fig. 4).

In the U.S., production comes from six mines located in New Mexico and Utah. While COVID had a minimal effect on the domestic potash market, U.S. production did decline to its lowest level of the past two decades in 2020 before gently increasing to an estimated 480,000 metric tons in 2021 (Jasinski, 2022).

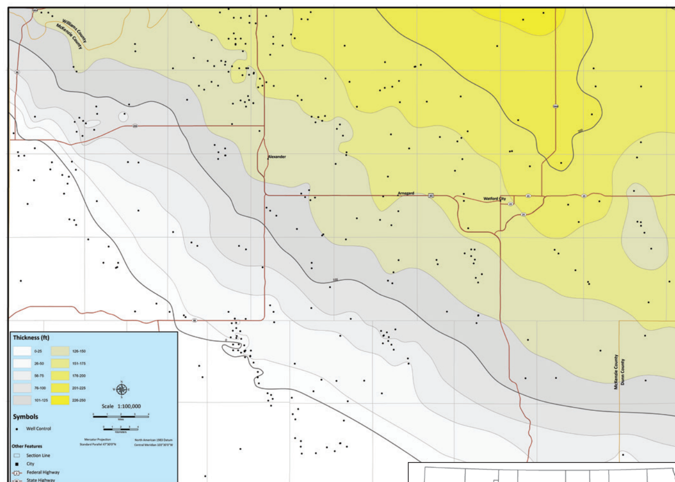

FIGURE 1.
Prairie Formation isopach map of the Watford City region from Geological Investigation No. 261 (Kruger, 2022).

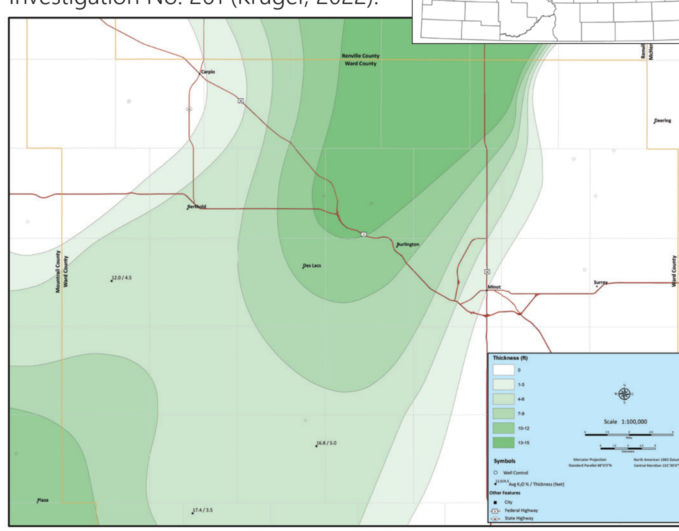

FIGURE 2.
White Bear potash member Isopach of the region surrounding Minot from Geological Investigation No. 258, sheet 2 of 3 (Kruger, 2021).

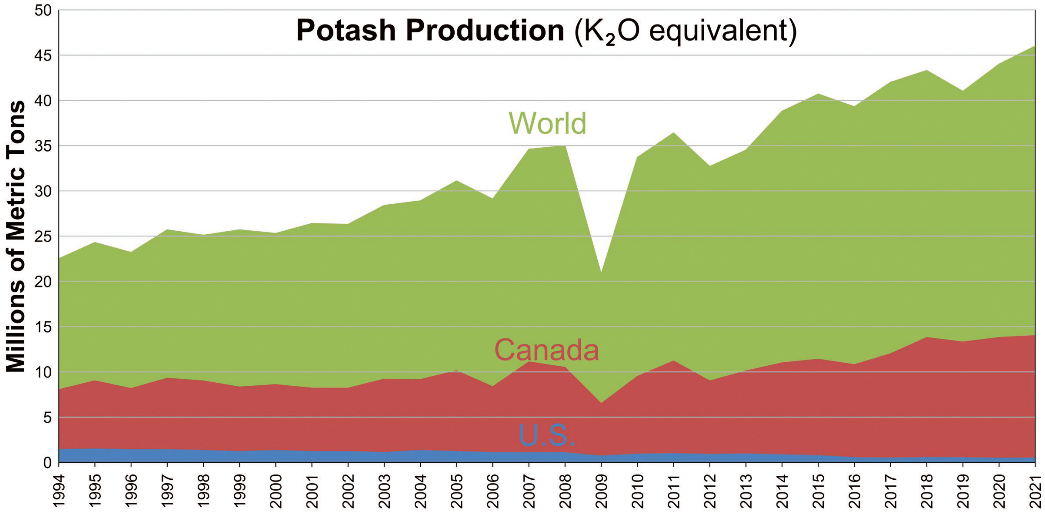

FIGURE 3. World, Canadian, and U.S. production of potash from 1994 through 2021. Source: U.S. Geological Survey Mineral Commodity Surveys.

POTASH LISTED AND DELISTED AS A "CRITICAL MINERAL"

In May of 2018, the United States Department of the Interior, pursuant to a Presidential Executive Order, published a report identifying 35 minerals and elements, including potash, as "critical minerals." As currently defined, a critical mineral is (1) identified to be a nonfuel mineral or mineral material essential to the economic and national security of the United States, (2) from a supply chain that is vulnerable to disruption, and (3) that serves an essential function in the manufacturing of a product, the absence of which would have substantial consequences for the U.S. economy or national security. This list is not a permanent designation of mineral criticality, but rather is updated at least every three years to represent current trends of supply, demand, concentration of production, as well as current policy priorities.

In November of 2021, a new draft list of critical minerals was posted in the Federal Register by the director of the United States Geological Survey for public comment. The draft list was based on directives from the Energy Act of 2020, which updated the methodology used to identify potential critical minerals. Potash was not included on the new list. While public comments were received which advocated for the inclusion of potash in the new listing, there were no inaccuracies found in the determinative quantitative evaluation and potash was left out of the final list in 2022 (United Stated Geological Survey, 2022). The mineral designation of critical is beneficial in the appropriation of federal funding for resource characterization and can also be advantageous in securing financing for new mining or expansion projects.

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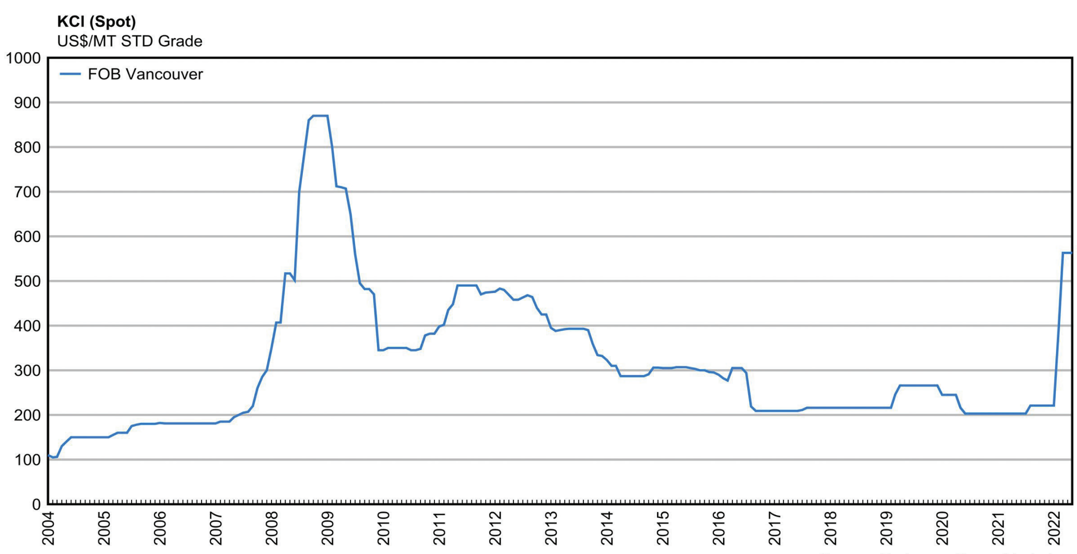


FIGURE 4. Potash spot market prices from 2004 through May of 2022. Sources: Fertecon, Green Markets.

RUMBLE ON THE PRAIRIE

THE 1909 NORTHERN GREAT PLAINS

EARTHQUAKE

THAT SHOOK NORTH DAKOTA

BY FRED J. ANDERSON

An estimated M 5.3 earthquake that occurred well over a century ago in the late evening hours of May 15, 1909 (May 16, 1909 UTC), is thought to have occurred in southeastern Saskatchewan (Horner and Hasegawa, 1978), near the junction of the borders of Montana and North Dakota. This historic temblor was felt by residents from Williston to Wahpeton and is the largest earthquake ever reported for our (N.D.) region and continental intraplate setting. The ground-shaking effects of this event were reported from as far north as Prince Albert, Saskatchewan, across North Dakota, and as far southeast as St. Paul, Minnesota. The highest intensity of ground shaking related to the earthquake was determined by seismologists in California, Montana (Mike Stickney-Montana Bureau of Mines and Geology), and British Columbia (Bakun and others, 2011) to have been focused near the town of Scobey in northeastern Montana; along a pre-existing northwest-trending fault near the border with Saskatchewan (Morgan, 2012). Although the event was recorded by seismographs over 4,000 miles away in Sweden and Germany (Bakun and others, 2010), determining an actual epicenter for this earthquake has been difficult and not without debate since there were no operating seismic stations in the area at the time (fig. 1). Felt reports were received and published

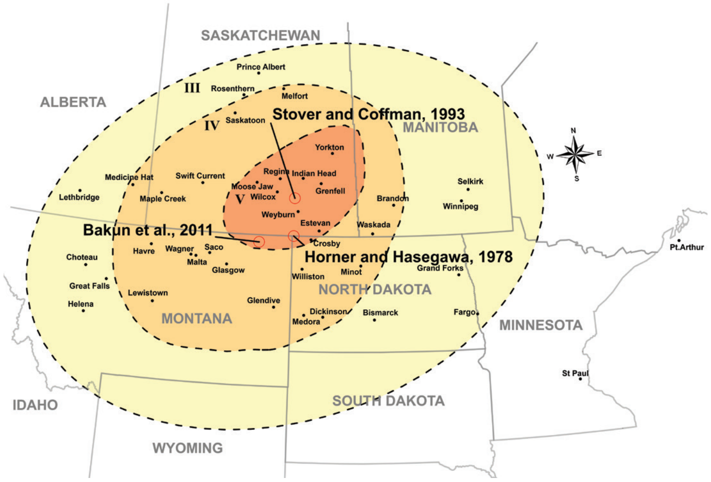


FIGURE 1.
Approximate felt area and possible earthquake epicentral locations determined from previous authors (red circles) from reported Modified Mercalli Intensity Scale values for the May 16, 1909 northern plains earthquake (adapted and modified from Nuttli, 1976 and Bakun and others, 2010).

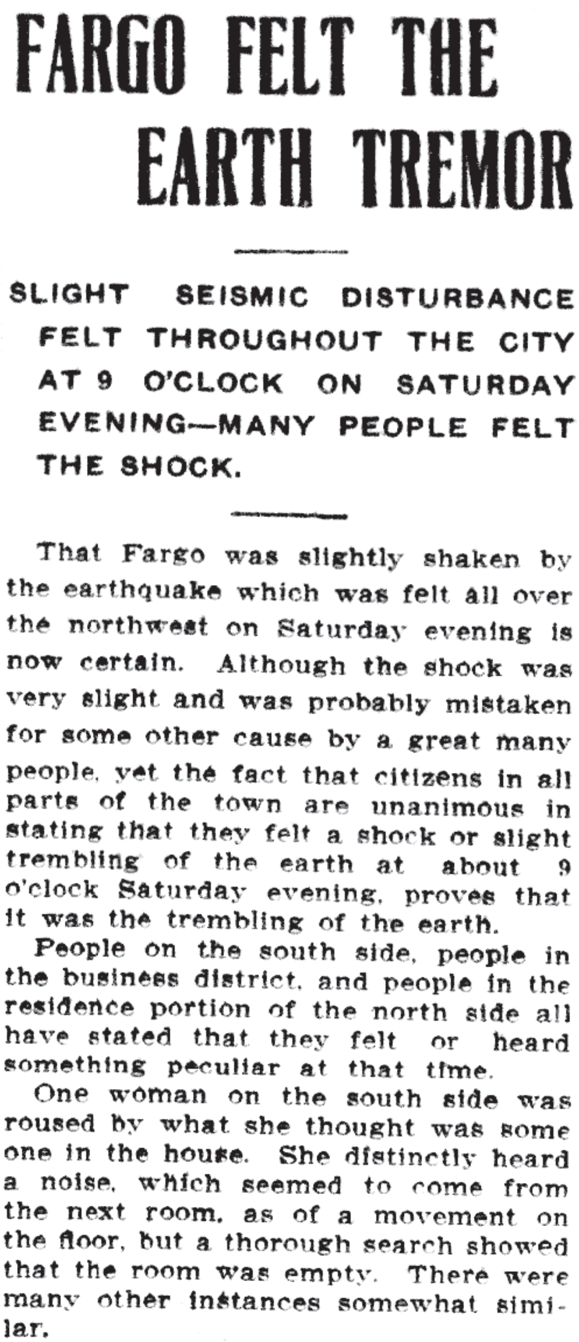
TABLE 1. Summary of reported newspaper accounts for North Dakota related to the May 16, 1909 Northern Plains Earthquake.

CITY	Intensity Value Assigned (MMI)	Reported Effects Felt from the Earthquake	Source of Report
Crosby	IV	"...distinct trembling of the earth...", "...jarring of buildings..."	Minot Weekly Optic – Fri., May 21, 1909
Williston	III	"...slight earthquake shock was felt..."	Williston Graphic – Thurs., May 20, 1909
Minot	IV	"...houses and beds shook..."	Minot Weekly Optic – Fri., May 21, 1909
Dickinson	IV	"...the falling of a wall which succumbed and crashed in like an egg-shell"	Dickinson Press – Sat., May 22, 1909
Medora	IV	"...slight earthquake shock was felt...", "Dishes rattled, houses shook and many were frightened..."	Fargo Forum and Daily Republican – May 17, 1909
Bismarck	IV	"...a distinct vibration, felt inside houses...a sort of trembling of floors and walls", "Dishes were rattled on the shelves and furniture shaken, and doors and walls quivered as they might in a heavy wind."	Bismarck Daily Tribune Tues., May 18, 1909
Fargo	III, IV	"...felt a shock or slight trembling of the earth."	Fargo Forum and Daily Republican May 17, 1909

MMI = Modified Mercalli Intensity Scale
Note: The Modified Mercalli Intensity Scale is a qualitative measure of perceived ground-shaking experienced during an earthquake and is variable depending on location.

in local North Dakota newspapers from the cities of Crosby, Williston, Dickinson, Bismarck, Fargo and reportedly Grand Forks, and were originally compiled into an isoseismal map by Nuttli (1976). Two additional accounts, recently uncovered from the Minot area by the author, have also been included (Table 1). Although this event was felt across a large area and apparently frightened many, little damage was actually reported (Bakun and others, 2011).

As mentioned previously, several felt reports of the earthquake were received by local newspapers in Crosby, Williston, Minot, Dickinson, Bismarck, and Fargo (fig. 2), and add some interesting color to the descriptions of the event.



FARGO FELT THE EARTH TREMOR

SLIGHT SEISMIC DISTURBANCE FELT THROUGHOUT THE CITY AT 9 O'CLOCK ON SATURDAY EVENING—MANY PEOPLE FELT THE SHOCK.

That Fargo was slightly shaken by the earthquake which was felt all over the northwest on Saturday evening is now certain. Although the shock was very slight and was probably mistaken for some other cause by a great many people, yet the fact that citizens in all parts of the town are unanimous in stating that they felt a shock or slight trembling of the earth at about 9 o'clock Saturday evening, proves that it was the trembling of the earth.

People on the south side, people in the business district, and people in the residence portion of the north side all have stated that they felt or heard something peculiar at that time.

One woman on the south side was roused by what she thought was some one in the house. She distinctly heard a noise, which seemed to come from the next room, as of a movement on the floor, but a thorough search showed that the room was empty. There were many other instances somewhat similar.

FIGURE 2.
Newspaper excerpt from the Monday evening edition of the Fargo Forum from May 17, 1909 reporting the event from eastern North Dakota.

In Crosby, "There was a distinct trembling of the earth which lasted from thirty seconds to a minute and strong enough to cause a jarring of buildings that was quite noticeable" (Minot Weekly Optic, Friday edition, May 21, 1909). In Williston, "A great many of our citizens were alarmed Saturday night when a slight earthquake shock was felt. Parties in dwelling houses and those living upstairs in the flats in the business portion of the city noticed more of a shock than others" (Williston Graphic, Williston, Williams County, N.D., Thursday, May 20, 1909).

In Minot, "Even the steadiest persons in town claim that their homes and beds shook Saturday night about 10 o'clock. One high school teacher jumped out of bed with visions of the whole South hill slipping down town…" (Minot Weekly Optic, Friday edition, May 21, 1909). In Dickinson, "The train dispatchers in the new Northern Pacific depot were frightened from their telegraph instruments and ran out of the building. They were prevented from returning to their keys for some time owing to the falling of a wall which succumbed and crashed in like an egg-shell" (Glasgow Democrat, Thursday, 20 May 1909, p. 5). It was also reported that, "Dishes rattled, houses shook and many were frightened" (Dickinson Press, May 22, 1909). In Medora, "A slight earthquake shock was felt here Saturday evening about 9 o'clock. Dishes rattled and pictures on the wall were disturbed." "Fargo was slightly shaken by the earthquake which was felt all over the northwest on Saturday evening is now certain" (Fargo Forum and Daily Republican, May 17, 1909. In Bismarck "For several seconds there was a distinct vibration, sufficiently distinct to be felt inside houses, and to cause a sort of trembling of floors and walls. Dishes were rattled on the shelves and furniture shaken, and doors and walls quivered as they might in a heavy wind." (Bismarck Daily Tribune, May 18, 1909, p. 4). In Fargo, "Although the shock was very slight and was probably mistaken for some other cause by a great many people, yet the fact that citizens in all parts of the town are unanimous in stating that they felt a shock or slight trembling of the earth at about 9 o'clock Saturday evening, proves that it was the trembling of the earth" (The Fargo Forum and Daily Republican, Fargo, N.D., Monday Evening, May 17, 1909, page 8).

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Small Exhibits, BIG IMPACT

BY BECKY BARNES AND CLINT A. BOYD

Since its inception in 1990, one goal of the North Dakota State Fossil Collection is to establish fossil exhibits in towns across the state so that people do not have to travel for hours to see and appreciate our prehistoric past (Hoganson, 2005). This program continues to expand, with fossils from our collection contributing to over two dozen exhibits across the state (fig. 1: Person and Boyd, 2016; Boyd, 2017). We frequently revisit these exhibits, ensuring everything is still in good condition and sometimes swapping in new fossils to keep the exhibit fresh. The overarching goal, as always, is continuing to find new places to set up fossil displays in areas of the state that currently lack an existing display. Over the past few years, we've had good success with this program, both in terms of updating existing exhibits and finding locations for new exhibits.

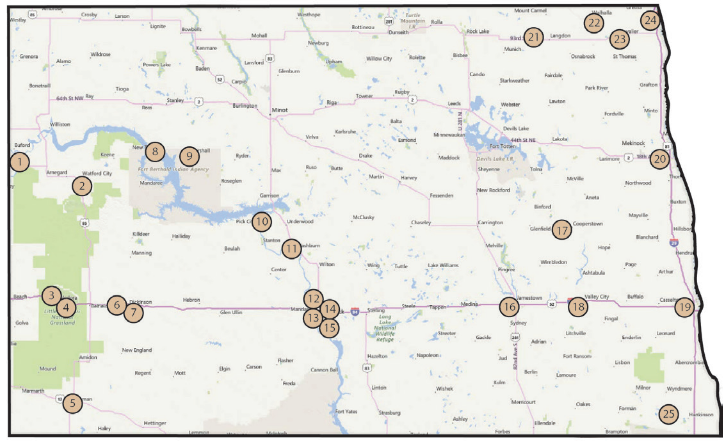

FIGURE 1.
Paleontological and geological exhibits throughout North Dakota that the North Dakota Geological Survey paleontological resource management program has assisted in developing as a part of the "A fossil exhibit in every town" program.
Background layer from Bing Road Maps. Key:
(1) Missouri-Yellowstone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

LIDGERWOOD PUBLIC LIBRARY

In the summer of 2019, we received a donated cast of a mounted skeleton of the small, plant eating dinosaur *Thescelosaurus*, a species from North Dakota that we've discussed in depth in a prior article (Boyd, 2016). While we were considering the best place to display this specimen, we were contacted by the Public Library in Lidgerwood, North Dakota asking if some of our staff could participate in a dinosaur-related kids reading event they were organizing. They were already going to impressive lengths to decorate the library, including assembling a large pterosaur (flying reptile) skeleton to hang from the ceiling (fig. 2). The timing was perfect, so we reached out and asked if rather than just having a paleontologist attend, what if we brought a whole dinosaur skeleton to the event! The skeleton is small, comes apart into seven pieces for easy transport, and can be assembled in minutes. We quickly arranged to have the specimen spend a few months on display at the library and set up an installation date. On Friday July 12th, 2019, the *Thescelosaurus* cast, nicknamed "Bert," was assembled on top of one of the library shelves, making it easily viewable to everyone and keeping it a safe distance away from the inquisitive hands of its young admirers (fig. 2).

The initial plans were to keep the skeleton there until the following spring, but those plans were paused as the COVID pandemic arrived in early 2020. As a result, "Bert" ended up spending almost three years at the Lidgerwood Public Library. During that time the Library added another dinosaur friend to keep "Bert" company, a *Tyrannosaurus rex*, and it was incorporated into numerous other events held at the library (fig. 2).

Eventually the time came for "Bert" to move on to another exhibit (see below), and in April of 2022 we disassembled and packed up the skeleton. However, during that visit plans were made to develop a permanent fossil display case in the library where a selection of fossils from across North Dakota could safely be exhibited.

That display will be updated periodically, removing some fossils and replacing them with a variety of new fossils so that there is always something new and exciting for visitors to stop in and see. It has been a great pleasure

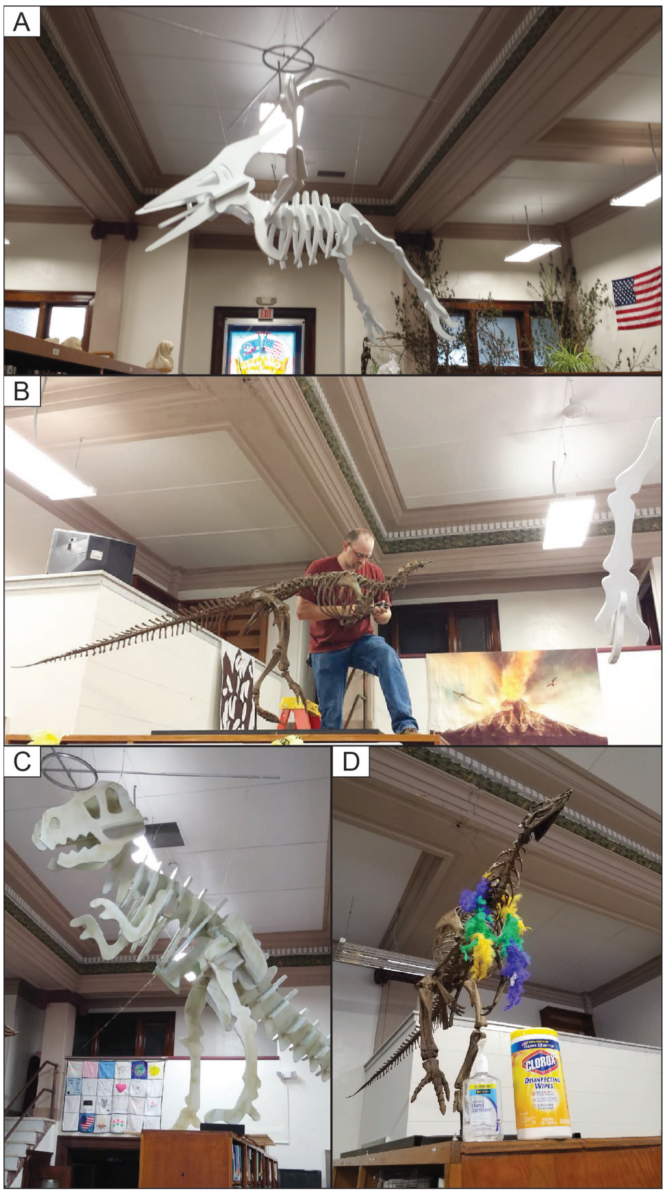

FIGURE 2.
Fossil exhibit at the Lidgerwood Public Library. **(A)** large toy pterosaur skeleton handing from the ceiling in the library. **(B)** paleontologist Clint Boyd installing the *Thescelosaurus* skeleton on top of a bookshelf. **(C)** large toy *Tyrannosaurus rex* skeleton added after the *Thescelosaurus* skeleton. **(D)** "Bert" the *Thescelosaurus* decorated for a mardi gras celebration. All images courtesy of the Lidgerwood Public Library.

for us to see this partnership expand from a short-term loan of a single specimen to a new permanent fossil exhibit far from our current exhibits.

BARNES COUNTY HISTORICAL SOCIETY MUSEUM

One of the larger fossil exhibits we helped develop in North Dakota is in the Barnes County Historical Society Museum in Valley City. In the spring of 2016, the museum and the NDGS Paleontology Program partnered to develop and install two large cases of Cretaceous fossils from North Dakota, including dinosaurs, mosasaurs, plants, and ammonites (Boyd, 2017). The centerpiece of that exhibit is a mounted cast of the skeleton of the three-horned dinosaur *Triceratops*. That exhibit is now over six years old, and the time has come to freshen it up a bit so that even those that have previously visited the museum have a reason to come back and check it out all over again. After thinking over our options, we decided that the quickest way to add a new feature to the exhibit was to give the *Triceratops* a friend to hang out with: a *Thescelosaurus*!

After picking up the *Thescelosaurus* from the Lidgerwood Public Library in April of 2022, we headed right over to Valley City for its next appointment. A quick study of the area around the *Triceratops* revealed that the location for the *Thescelosaurus* was under the larger dinosaur's tail. The skeleton was quickly assembled and "Gundy" the *Triceratops* now had a new friend (fig. 3). This addition is the first step in updating the fossil exhibits at the Barnes County Historical Society Museum, with plans in the works to change out some of the dinosaur fossils in the existing display case with some new material that will be sure to give the exhibit a fresh look. Until then, we encourage everyone to stop in a see "Bert" and "Gundy" for yourselves!

WALHALLA PUBLIC LIBRARY

Another example of a great fossil display in a smaller town in North Dakota is the mosasaur on display in Walhalla. This specimen was first loaned to the city and put on display decades ago, but over time the information surrounding the fossil was lost, and staff turnover meant that no one knew what the fossil was, or where it came from. It was eventually handed over to the Walhalla Public Library and stored in its case in a back room. Enter NDGS paleontologists Clint Boyd and Becky Barnes! In the fall of 2019, after driving up from Bismarck to check on the public fossil dig locality in the nearby Pembina Gorge and chatting with locals, we ran into the librarian Barbara, who asked if we could take a look at what she thought was a turtle fossil. Heading to the back room of the museum, we saw a plaster jacket with mosasaur bones in it – which looked like a turtle shell flipped upside down. Lifting the jacket up to inspect it for identifiers, we saw a telltale NDGS field number – this was the first mosasaur specimen we collected from the Pembina Gorge! It had been cleaned and brought up for display years ago, but over time the information about the specimen had been lost. This is exactly why we label all of our fossils with specimen numbers in case they get separated from their loan paperwork!

After discussion, it was decided that the mosasaur should be put on display (with more labels and contact information) in the Library – a wonderful public place where adults and kids alike gather to learn. We were able to load the fossil up and transport it

FIGURE 3. Installation of the *Thescelosaurus* skeleton next to "Gundy" the *Triceratops* at the Barnes County Historical Society Museum. **(A)** paleontologist Clint Boyd (blue shirt) and Museum Curator Wes Anderson (black shirt) installing the hind legs of the skeleton. **(B)** Installation of the front arms of the *Thescelosaurus*. **(C)** Tightening up the final screws on the *Thescelosaurus* skeleton as it takes its place next to "Gundy."

FIGURE 4.
The opening of the mosasaur exhibit at the Walhalla Public Library in January of 2020. **(A)** the newly cleaned mosasaur vertebrae in their supportive plaster jacket and associated information cards. **(B)** paleontologist Clint Boyd shows off a Paleocene turtle fossil to the kids. **(C)** paleontologist Becky Barnes reads her newly completed kids book "PrehiStories: Mosasaur" to the kids.

back to our lab in the North Dakota Heritage Center & State Museum in Bismarck where we did some additional cleaning and added a new jacket to provide additional support for the fossils. That work was completed early in 2020, just as Becky also completed a kids book about mosasaurs in North Dakota (PrehiStories: Mosasaur: Barnes, 2020). This made for a great opportunity to combine the opening of the updated mosasaur display with a reading of the new kids book. Illustrations from the book were added to the informational cards in the exhibit to add a splash of color and help draw attention to the exhibit. In late January the Library invited families and kids in the area to attend their weekly reading event and provided paleontology themed snacks while our paleontologists read the new book aloud to the families present, showed off a variety of other fossils from North Dakota, and unveiled the new exhibit to a crowd of excited kids and parents (fig. 4). When it was suggested that the specimen should have its own nickname one attendee suggested "Walhalla George from the Pembina Gorge" and the name was quickly adopted. George remains on display in Walhalla, just down the road from where its fossils had rested for 80 million years.

A FOSSIL EXHIBIT IN YOUR TOWN?

Looking forward, we are in talks with a few locations to possibly place new fossil exhibits and making plans to expand and/or update some of our current exhibits. That being said, we're always looking for new places to get some fossils out on display for everyone to see. Have an idea for a location in your community where a fossil exhibit could be installed, either on a long-term or short-term basis? Maybe you have an idea for the next place our "Bert" skeleton should spend some time? Please reach out to us and start a conversation! The North Dakota State Fossil Collection exists for the benefit of all North Dakotans and our fossils best serve that purpose when they're out for everyone to see!

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LITHIUM EXPLORATION IN THE WILLISTON BASIN

AND THE POTENTIAL OF MADISON BRINE WATERS IN WESTERN NORTH DAKOTA

BY TIMOTHY O. NESHEIM

INTRODUCTION

Lithium is utilized for a variety of applications including pharmaceuticals as well as automotive/industrial lubricants. Most commonly, however, lithium is a key component within batteries. Demand for electric vehicles has been steadily rising over the past several years, vehicles that require large batteries and substantial amounts of lithium. Assuming the demand for electric vehicles continues to climb, the demand for the lithium necessary to construct the electric vehicle batteries will also likely increase.

LITHIUM EXPLORATION IN THE WILLISTON BASIN

Exploratory drilling for lithium in subsurface brine waters of the Williston Basin was initiated during 2021. Prairie Lithium recently drilled the first reported lithium brine exploration well in the history of Canada and the greater Williston Basin, which reportedly encountered 53m of net pay (Businesswire, 2021). The company holds mineral permits over 360,000 acres in southeastern Saskatchewan and drilled their exploration well near Torquay, just across the border from Divide County in northwestern North Dakota (fig. 1).

Publicly available data and information on Prairie Lithium's exploration project is still limited. However, the Saskatchewan Geological Survey has been intermittently conducting brine water analyses from oil and gas wells over the past two decades, including two recent sampling projects with water samples extracted from wells proximal to Prairie Lithium's area of exploration (Rostron et al., 2002; Jensen, 2012; Jensen and Rostron, 2017; 2018).

Brine waters sampled and analyzed by the Saskatchewan Geological Survey from reservoirs spanning the Birdbear, Duperow, Madison, Red River, Torquay (Three Forks), and Winnipegosis Formations yielded lithium concentrations ranging from 4 to 78 mg/L (Jensen and Rostron, 2017; 2018). The highest reported lithium concentrations were samples extracted from the Duperow (41-78 mg/L) and Winnipegosis (45-63 mg/L) Formations, both of which extend southwards into western North Dakota.

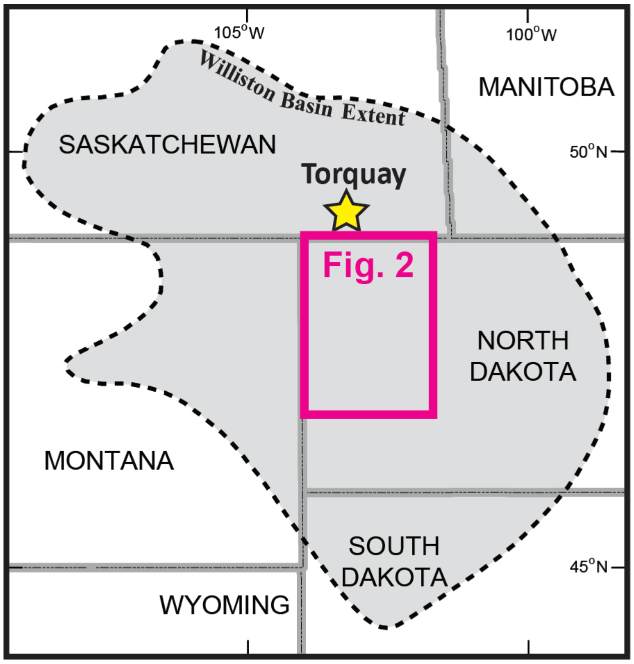

FIGURE 1.
Williston Basin extent map showing the approximate location of Torquay, Saskatchewan and the Prairie Lithium exploration area as well as the Figure 2 map area.

LITHIUM POTENTIAL IN NORTH DAKOTA

More than 3,000 water analyses from Madison Group reservoirs have been compiled within the North Dakota Oil and Gas Division database (NDOGD, 2018). Preliminary review of those 3,000+ analyses revealed 31 analyses that included lithium concentrations from a total of 24 wells (Table 1, fig. 2). The remaining ~99% of the water analyses did not reportedly test for lithium. While the reasoning for why these 31 water analyses included lithium is unknown, all 31 of these Madison analyses were completed within a limited, ~2 ½ year time window of April 1963 to August 1965 (Table 1).

The 31 Madison water samples were from 24 oil and gas wells distributed across six counties spanning western North Dakota, half (12) of the wells were from Burke County.

The reported lithium concentrations from the brine waters produced from Madison reservoirs ranged from 1 to 345 mg/L (Table 1). Three of the 4 samples with the highest reported lithium concentrations (>80 mg/L) cluster together in Burke County (fig. 2). The two highest reported lithium concentrations are from wells #3349 in Burke County (345 mg/L) from the Rival subinterval (upper Frobisher-Alida) and #3700 of Stark County (200 mg/L) from the Midale/Berentson subinterval(s) of the lower Ratcliffe Interval (fig. 3). These concentrations are several times higher than any of the analyses reviewed from southeastern Saskatchewan (Rostron et al., 2002; Jensen, 2012; Jensen and Rostron, 2017; 2018) as well as southwestern Manitoba (Nicolas, 2017), and therefore may represent future opportunities for solution mining of lithium from Madison brine waters in North Dakota.

All of the water analyses reviewed in this article are publicly available in the respective oil and well wells files through the North Dakota Industrial Commission. Additional water geochemistry data containing lithium concentrations of other, non-Madison stratigraphic units may also be available publicly for review. Lithium exploration and solution mining potential likely exists in the other, non-Madison stratigraphic units such as the Duperow and Winnipegosis Formations.

TABLE 1. General well information (well numbers and location) with Lithium (Li) concentrations and related information from Madison brine water analyses.

NDIC Well #	API Well Number	Location			Analysis Date	Test Interval (ft)		Li (mg/L)	NaCL (mg/L)
		Sec	Twp	Rng		Top	Bot		
2186	33013002250000	35	163	92	01-Nov-63	6,140	6,163	**10**	309041
2611	33053004510000	14	145	101	14-Sep-64	9,436	9,440	**24**	323652
3135	33013004770000	15	162	92	24-Apr-63	6,200		**164**	320735
3349	33013005240000	10	162	92	03-May-63	6,200		**85**	312996
3349	33013005240000	10	162	92	09-Jul-65	6,350	6,373	**345**	290920
3353	33061001710000	28	158	91	17-Apr-63	7,776	7,830	**1**	306531
3367	33013005320000	14	162	92	24-Apr-63	6,200		**164**	320735
3367	33013005320000	14	162	92	20-Jun-63	6,336	6,358	**4**	327051
3372	33013005330000	4	162	92	25-Jun-63	6,327	6,351	**5**	93821
3372	33013005330000	4	162	92	25-Jun-63	6,327	6,351	**20**	293549
3372	33013005330000	4	162	92	25-Jun-63	6,327	6,351	**20**	283774
3441	33023000790000	3	162	102	07-Nov-63	6,877	6,899	**10**	320822
3446	33013005560000	4	159	90	16-Nov-63	7,178	7,218	**8**	214257
3455	33013005580000	25	161	92	26-Dec-63	7,100	7,114	**1**	51992
3455	33013005580000	25	161	92	26-Dec-63	7,100	7,114	**4**	46705
3456	33023000800000	35	163	103	30-Nov-63	6,617	6,641	**20**	311286
3456	33023000800000	35	163	103	30-Nov-63	6,638	6,671	**20**	316151
3498	33013005700000	2	161	93	23-Feb-64	6,959	6,970	**4**	125601
3510	33013005740000	12	161	94	16-Mar-64	7,475	7,531	**10**	172302
3540	33061001730000	30	158	88	08-May-64	6,860	6,907	**10**	300360
3575	33061001740000	3	157	89	09-Jun-64	7,048	7,126	**10**	308312
3576	33105006480000	14	159	103	09-Jun-64	7,724	7,767	**10**	327356
3578	33013005870000	13	161	94	19-Jun-64	7,555	7,615	**10**	266534
3581	33061001750000	5	156	88	23-Jun-64	6,979	7,029	**10**	273590
3590	33013005910000	33	162	93	17-Jun-64	7,028	7,053	**10**	270108
3590	33013005910000	33	162	93	17-Jun-64	7,044	7,094	**10**	289805
3596	33023000830000	35	163	103	29-Jun-64	6,630	6,658	**10**	311533
3597	33023000840000	25	162	103	14-Jul-64	6,928	6,995	**10**	267764
3604	33013005950000	17	159	90	20-Jul-64	7,229	7,262	**10**	312682
3604	33013005950000	17	159	90	20-Jul-64	7,262	7,312	**10**	304068
3700	33089000170000	29	140	96	10-Nov-64	8,767	8,814	**200**	338449
3909	33023000900000	22	163	103	10-Aug-65	6,564	6,584	**4**	278785

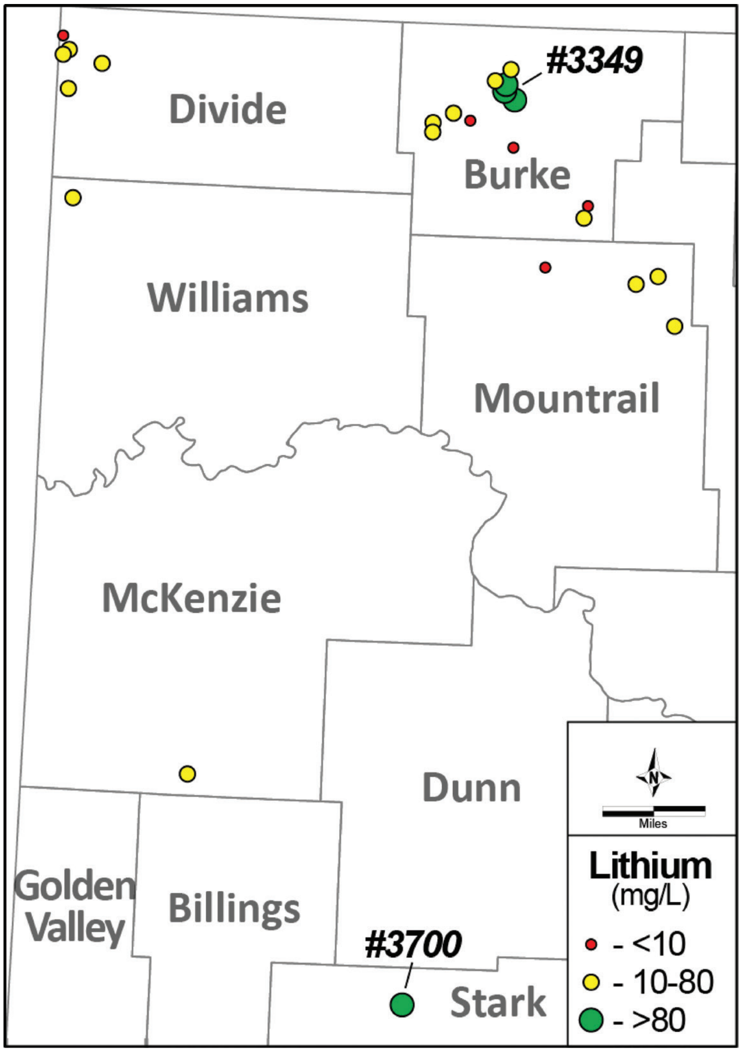

FIGURE 2.
County map of western North Dakota with the distribution of 24 wells with Li concentrations measured from brine waters collected from Mississippian Madison Group reservoirs. For wells that contain multiple (2-3) Madison water analyses with reported lithium concentrations, the maximum Li concentration is reflected by the bubble map.

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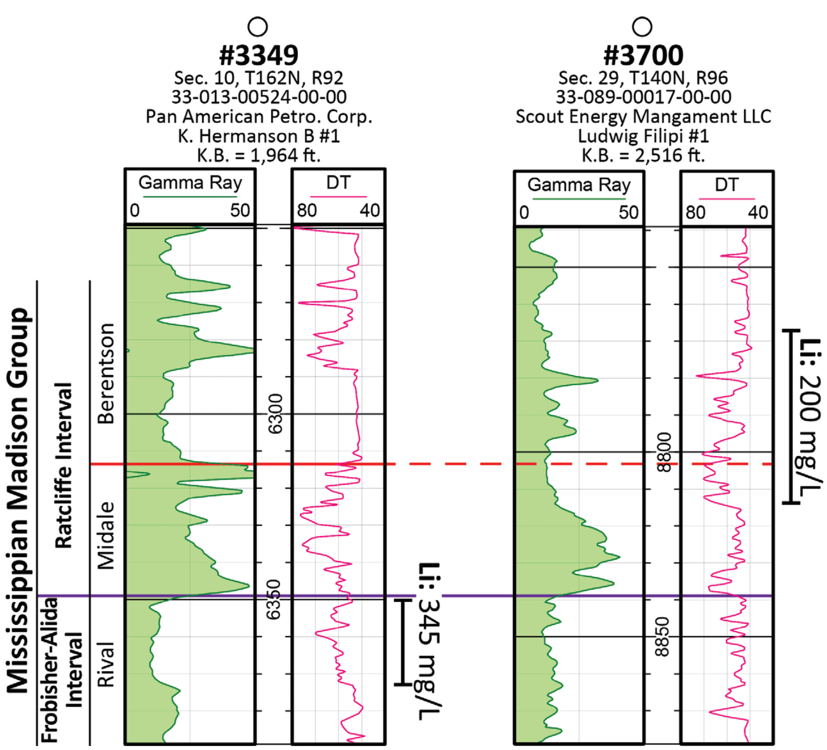

FIGURE 3.
Stratigraphic cross sections of wells #3349 and #3700 showing the reported water sample interval along with the reported lithium concentrations. Well locations are indicated on the Figure 2 map.

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.

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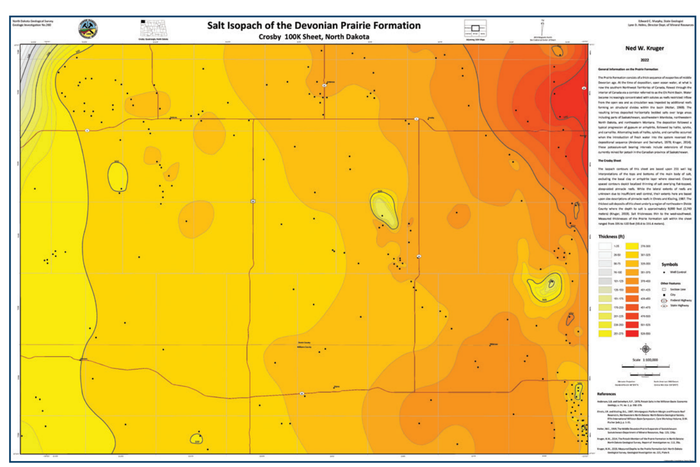

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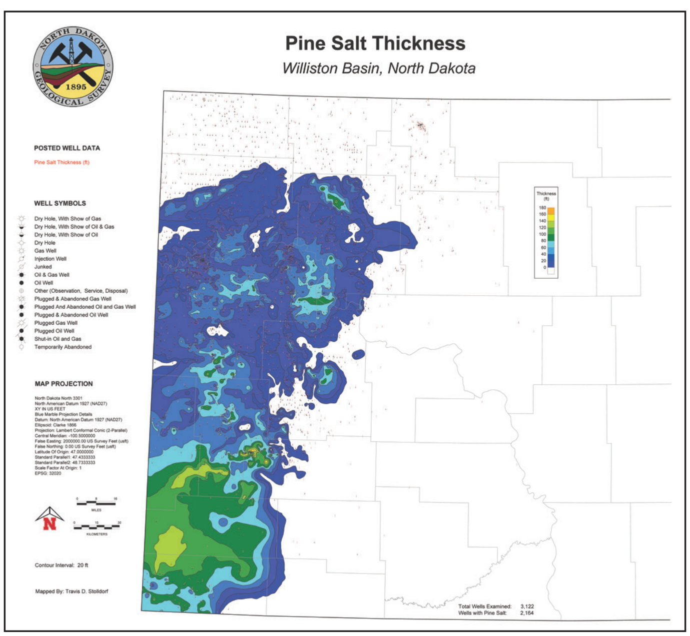

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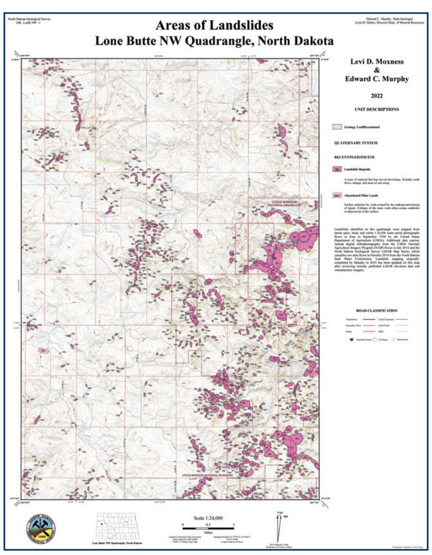

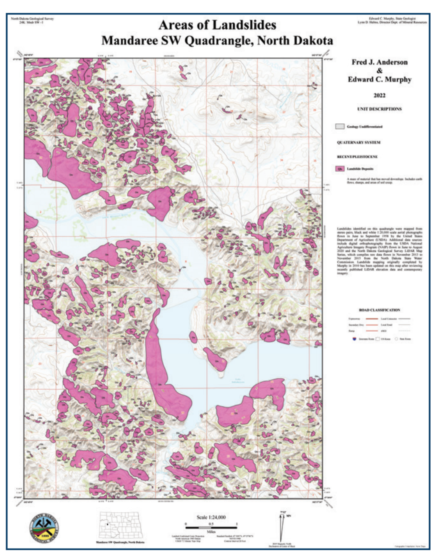

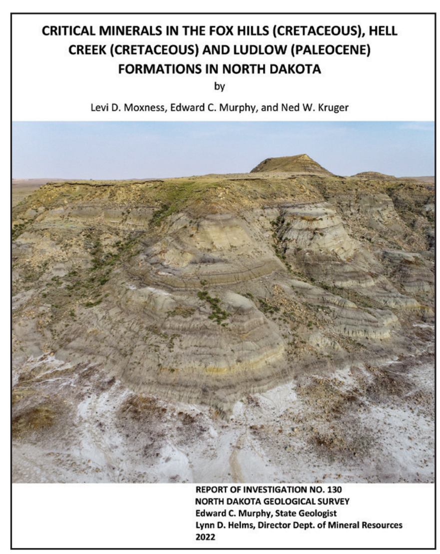

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