The First Statewide Landslide Dataset

NDGS completes initial landslide mapping for North Dakota

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The North Dakota Geological Survey (NDGS) published its first 1:24,000-scale landslide inventory maps in 2003. Now, some 18 years, 1,750 maps and 37,161 landslides later, full coverage of the state is available (www.dmr.nd.gov/ndgs/landslides/). The surface of North Dakota hosts a plethora of mass-wasting landforms, from continuous landslide complexes covering several square miles to small areas of shallow soil creep, from fluidized mudflows to slowly rotating slump blocks of bedrock. Large or small, fast or slow, landslides have the potential to snap fiber optic and electric cables, break water, sewage, oil and gas pipelines, or undermine building foundations, roads, and railways. This mapping dataset provides a foundational geohazards layer for infrastructure planning in the state of North Dakota, identifying areas for avoidance or advanced geotechnical assessment. Although coverage is complete, updates are ongoing as new technology reveals previously obscured slope failures.

Previous Geo News articles have described the occurrence of these features in North Dakota, provided updates on the NDGS landslide mapping program, and summarized field investigations of recent collapses impacting infrastructure (Murphy, 2017; Moxness, 2019; 2020). The completion of a first statewide coverage comes as a result of a concerted effort of over the past five years, during which time over 1,300 maps were produced covering over 75% of the state (Table 1). Developed areas were prioritized for mapping (major cities, oil and gas fields, wind farms, pipeline routes), followed by areas well-known for slope failures: the Little Missouri badlands and major hydrologic corridors (banks and valley walls of the Missouri, Pembina, Red, and Sheyenne rivers). The remaining areas included large areas of the glaciated plains and Missouri coteau, regions which are low-relief and largely devoid of slopes steep enough to fail, which has expedited mapping since 2019 (fig. 1).

	Percentage of North Dakota Mapped	Number of Landslides Identified	Total Landslide Area (acres)	Average Landslide Size (acres)
November 2021	**100%**	**37,161**	**271,460**	**7.3**
January 2019	49%	22,543	200,983	8.9
January 2017	25%	11,077	116,500	10

Table 1. Updated statistics of the NDGS landslide inventory mapping program. Recent mapping has been expedited as the program moved through areas of the state with lower landslide densities.

The NDGS has also updated about half of nearly 300 older maps that were published prior to LiDAR (Light Detection and Ranging) availability. Digital elevation models produced from LiDAR data provide unprecedented detail to mappers, especially in heavily wooded areas (Moxness, 2019; Maike, 2021). For these early NDGS landslide maps, three-dimensional visualization of the landscape was accomplished solely through stereo projection of black and white 1:20,000-scale aerial photographs from the 1950s and '60s. By today's standards, even much of the digital imagery as recent as the mid 2010's is considered low-resolution. Despite the limitations of imagery quality and analogue mapping, landslide maps published pre-2017 are still remarkably comprehensive. The areas that do see significant increases in the number of identified slides during remapping with LiDAR are wooded slopes (LiDAR filters out vegetation) and smaller failures more easily verified by digital zoom (fig. 2). Updates to Phase I maps are likely to add thousands more landslides to the statewide inventory.

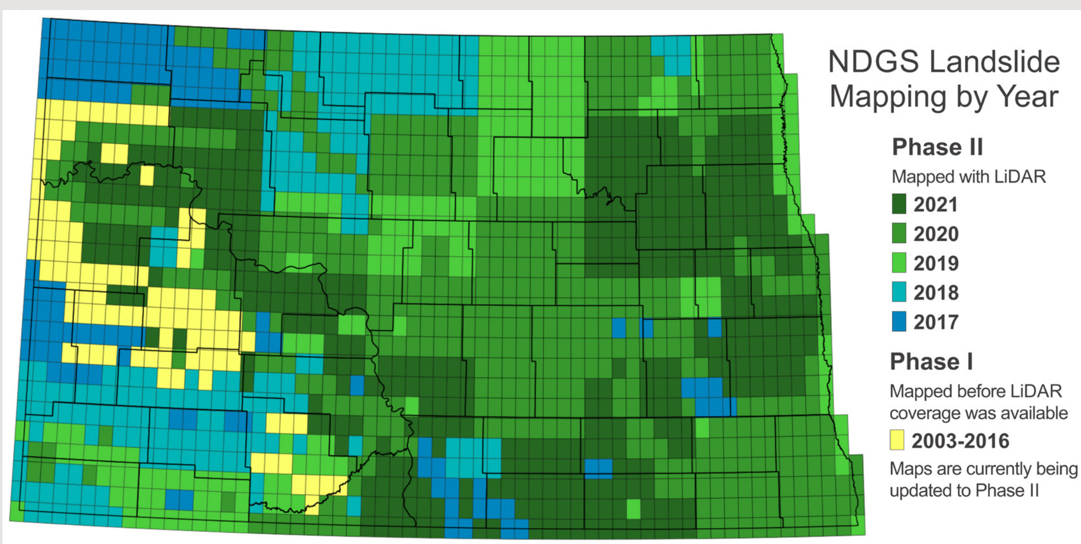

Figure 1. Date of publication for NDGS 1:24,000-scale landslide maps. Quadrangles in yellow are being updated with more recent aerial imagery and elevation models.

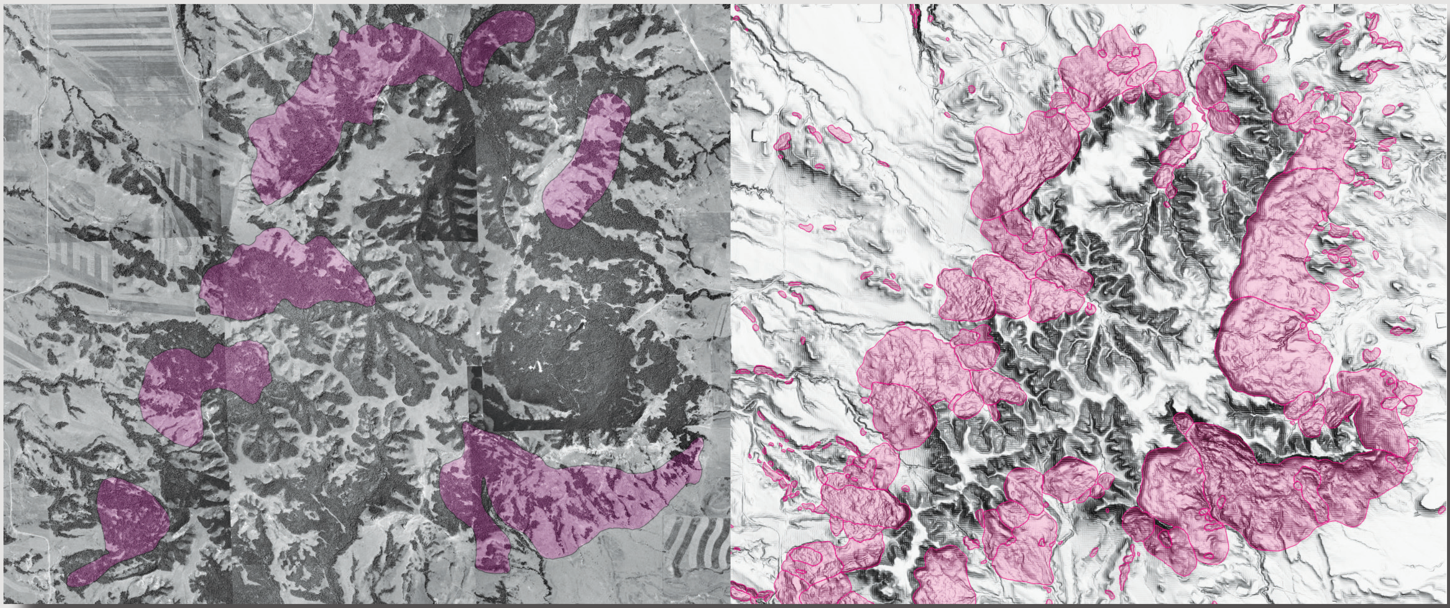

Figure 2. Phase I mapping (left) of the Killdeer Mountains on 1958 aerial photographs. The expression older landslides around the high buttes of western ND is often obscured by heavy tree cover and muted by draped colluvium in photographs, but the broken terrain is visible on bare earth LiDAR hillshades used during Phase II mapping (right). Smaller areas can be easily inspected using digital zoom.

Although updates are still to come for the statewide landslide layer, the complete coverage provides some initial statistics on the occurrence of these features in North Dakota. The type of the landslide and identification of the material that has failed could be precisely categorized through a much slower mapping process that included slide-by-slide field-based characterization

Figure 3. A slump, delineated by the dashed line, along the Cannonball River six miles (10 km) southwest of Elgin. Arrows indicate direction of movement. The length of the headscarp (the uppermost wall of uncollapsed bedrock) is approximately 4000 feet (1200 m). Photo looking to the south.

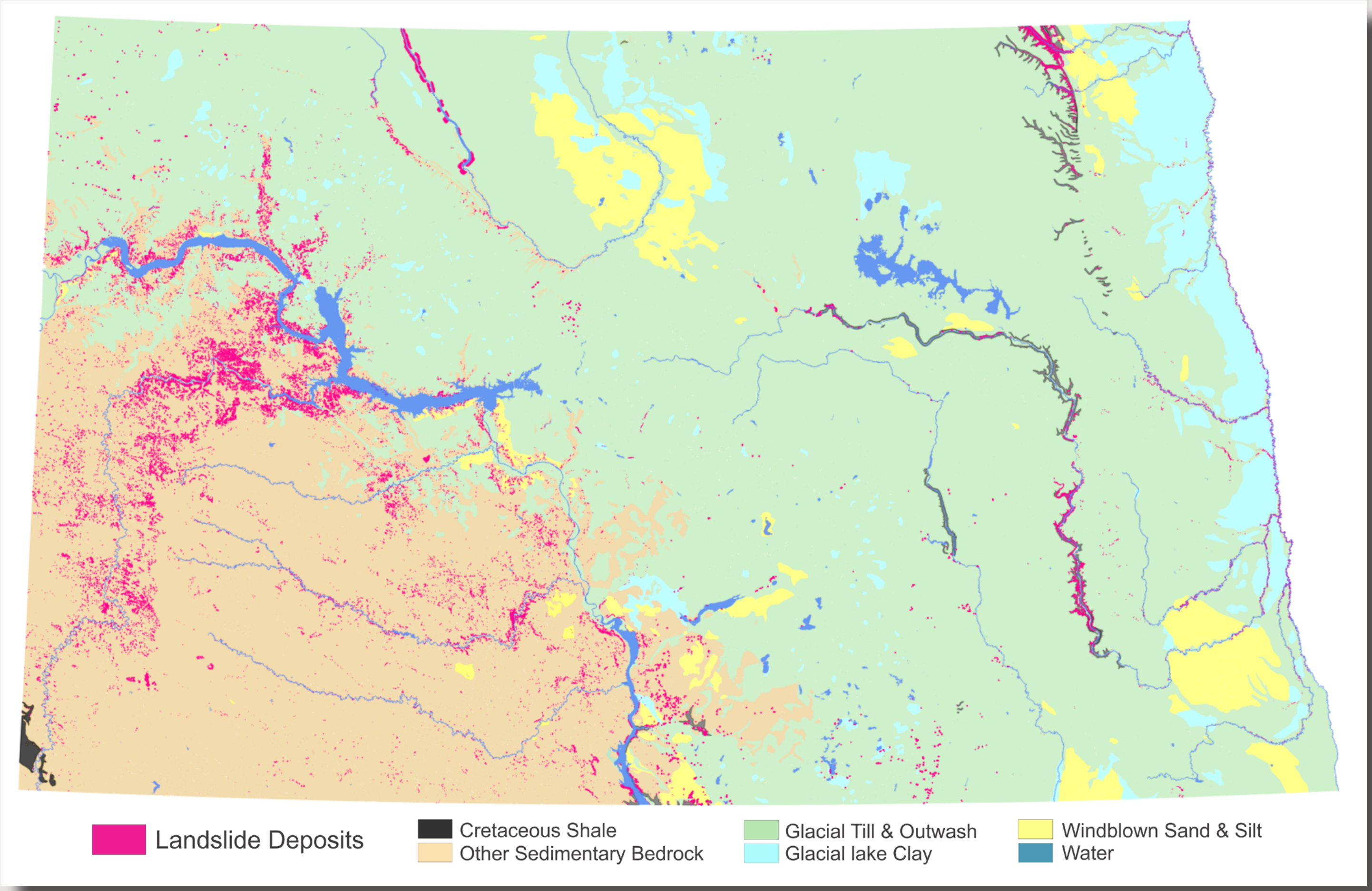

Figure 4. Map of landslides in North Dakota relative to the major surficial lithologic groups modified from Clayton (1980).

(fig.3), but the NDGS elected to first focus on completing the spatial mapping component, especially considering users would still need to verify the details on the ground as part of a complete pre-construction site evaluation. Some lithologic information can be inferred, however, including the foremost question to geologists and engineers: which lithostratigraphic units are most prone to failure? Geotechnical professionals familiar with local geohazards can likely guess the most problematic rock types, but by overlaying landslide and surface geology data, we can roughly quantify these relationships for the entire state for the first time.

The NDGS landslide dataset is 1:24,000 scale. Only 8% of North Dakota surface geology is currently mapped at the equivalent scale, and units are not synonymized across the many authors, so the simplest surficial geologic dataset is the statewide 1:500,000 geologic map (Clayton, 1980). Although the scales vary greatly, overlaying the two datasets still captures the major lithologic correlations. Clayton's statewide map also includes 38 mapping units with genetic subdivisions for the Quaternary; more detail than is needed for this exercise. Figure 4 shows the distribution of North Dakota landslides by major lithology type. Table 2 further subdivides out the major bedrock formations. Note the Pierre, Niobrara, and Carlile Formations are still combined under Cretaceous shales. The Golden Valley Formation, White River Group, and other isolated mid/upper-tertiary units are combined. Coarse glacial (all till and outwash), glacial lake clay, and windblown sand units are grouped separately. Holocene pond and river sediment includes more recent sediment along the banks of modern ponds, streams, and rivers.

Despite only compromising about half a percent of North Dakota's surface, outcrops of shale in the Pembina Gorge and Sheyenne Valley compromise over 10% of the landslide area in the state. This unit thus experiences a failure rate about three times any other in North Dakota. While the poorly cemented swelling clays within shale do make it a uniquely weak lithology, most of the slope failures associated with this unit occur where outburst floods at the end of the last ice age carved deep meltwater trenches. Outcrops of shale in the far southwestern corner of the state form gently rounded hills, so it is the combination of steep valley walls and weakly lithified muds that make these two eastern areas especially prone to creep, translational landslides, and earthflows.

Another lithologic group that makes up only a small amount of the state (0.75%) but contains a high proportion of landslides is the Golden Valley Formation and younger bedrock (the White River Group and undivided Miocene and Pliocene units). Combined, these formations comprise many of the tall buttes of southwestern North Dakota (Sentinel Butte, Bullion Butte, White Butte, the Killdeer Mountains, etc.). Most of these buttes are preserved because of a highly resistant caprock in these units (Murphy and others, 1993). When that caprock collapses (one

Lithostratigraphic unit	Percent of ND surface (Clayton, 1980)	Number of landslides within unit	Percent of all landslides (by area)	Percent of area failed
Cretaceous Shales	0.58%	1694	10.08%	**13.84%**
Younger bedrock (high buttes)	0.75%	1298	4.47%	**4.75%**
Sentinel Butte Fm.	12.76%	18259	38.01%	**2.36%**
Bullion Creek Fm.	5.87%	5313	12.57%	**1.70%**
Quaternary Pond & River	5.84%	3448	11.47%	**1.56%**
Cannonball Fm.	2.10%	1770	3.31%	**1.25%**
Fox Hills Fm.	1.49%	661	2.04%	**1.08%**
Hell Creek Fm.	1.80%	1342	1.97%	**0.87%**
Ludlow Fm.	0.91%	527	0.96%	**0.84%**
Slope Fm.	1.84%	867	1.86%	**0.80%**
Glacial Till & Outwash	56.74%	4567	12.43%	**0.17%**
Glacial Lake	4.99%	432	0.50%	**0.08%**
Windblown Sand & Silt	4.32%	512	0.33%	**0.06%**

Table 2. Landslides in North Dakota by bedrock formation and major Quaternary lithogenesis.

of the few examples of rockfalls in the state) the less resistant lithologies below erode into steep cliffs, which in turn are prone to large rotational slumps.

Over half (50.58% by area) of the landslides in the state occur in the Sentinel Butte and Bullion Creek Formations, which are the primary bedrock units outcropping in North Dakota at 12.76% and 5.87% of the state's surface, respectively. The Missouri River and its tributaries erode the alternating sandstone, siltstone, mudstone, claystone, and lignite beds, which are moderately-resistant units that form the classic rugged terrain of the Little Missouri Badlands. These rocks are prone to failure via large rotational slumps, especially along the eastward course of the Little Missouri River, which experienced rapid downcutting during the last glacial maximum as glacial ice rerouted its course. The fact the Little Missouri River primarily cut through these two formations, creating steep slopes to fail, may explain why these formations have failed more often (2.36% of Sentinel Butte and 1.70% of Bullion Creek area is failed slopes) than lithologically similar ones (0.80% to 1.25% for the Slope, Cannonball, Ludlow, Hell Creek, and Fox Hills Formations). The correlation between slope height and landslide density was noticed in the earliest stages of landslide mapping (Murphy, 2000).

Glacial lithologies are some of the least likely to contain landslides. Glacial till and outwash alone make up over half of the state's surface area and does fail where rivers and streams incise it, but generally glaciers flattened the terrain and coarse glacial sediment is a fairly stable material. Glacial lake sediment, despite being an extremely weak material (unconsolidated clay and silt), occurs on the flattest landscapes in the state and thus there is little potential for movement. The major rivers and streams that cross the Red River Valley do have abundant cut bank failures and lateral spread along their channels, but these predominantly occur in Quaternary Pond and River sediment, which also occurs in the bottom of other major valleys. Landslides within this unit reflect normal collapses along the banks of rivers across the state. The least likely lithology to collapse in a landslide is windblown sand and silt, which is a non-cohesive material that is more likely to erode than fail as a mappable mass.

The links between the rock and sediment types of North Dakota and the distribution of its landslides are apparent but are only fully contextualized when also considering the state's geologic history. The story of landslides in North Dakota is largely a story of slopes, carved by glacial ice sheets and meltwater into the landscape we see today. Work by the NDGS in coming years will completely update the 1:24,000-scale picture, and has already began to identify which of these 37,000+ areas may still be active.

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