# Sieve Analysis of Selected Late-Cretaceous and Tertiary (Paleocene) Bedrock Sandstones in North Dakota for Potential use as Proppant

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## Abstract

In 2018, a study was conducted on the proppant potential of Late-Cretaceous to Middle-Tertiary sandstones in south-central and western North Dakota. This preliminary evaluation was done to determine the usefulness of these sandstones in the hydraulic fracturing of oil and gas wells in the Williston Basin. Gradational (sieve) analysis was performed on 19 samples from 14 locations revealing that these sandstones are dominantly well-sorted medium-grained (40/70) and fine-grained (70/140) sands.

## Acknowledgements

The authors would like to thank the North Dakota Department of Trust Lands for access to the outcrops sampled in this report. Cartographic support was provided by Mr. Navin Thapa, GIS Specialist with the North Dakota Geological Survey. Sand analytical services (sieve analyses) were provided by Golder Associates in Houston, Texas.

## Author's Note

Recently the oil and gas industry has relaxed proppant testing specifications in part of the U.S. in favor of more regional or local proppant sand source utilization. This preliminary evaluation was conducted in response to requests by companies in the proppant sand industry and the North Dakota Oil and Gas Industry to further investigate the state's sand resources for potential use as proppant in the hydraulic fracturing of oil and gas wells in the Williston Basin. The limited evaluation and testing performed as a part of this investigation, which consisted of photomicrography and sieve analysis, is summarized herein in order to expeditiously provide the general characteristics of these sandstones. More detailed studies will follow this report.

Figures 6, 9, 10, 11, 12, and 13 are 20 megapixel images acquired using the North Dakota Geological Survey's DJI Phantom 4 Pro drone. Pictures were collected by FAA Part 107 Certified Remote Pilot, Chris Maike.

Cover photo: An outcrop of the middle Sentinel Butte Formation in central McKenzie County. Five feet of fine-grained sandstone is horizontally interbedded with light brown mudstone at the base of the exposure and transitions upwards to 10 feet of well-sorted, trough cross-bedded sandstone, which contains dark gray mud in its uppermost 2-4 feet. At this locality, this channel sandstone is moderately well cemented and overlain by 15 feet of brown, orange, yellow, and gray mudstones, siltstones, sheet sandstones, and thin lignites containing concretions and petrified wood typical of much of the Fort Union Group in western North Dakota.

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## BACKGROUND

### Introduction

The evolving success of the Bakken\Three Forks oil play in North Dakota, through hydraulic fracturing and the placement of proppants in fractures during the stimulation of completed wells, has created an unprecedented demand for natural proppants in the Williston Basin and across the nation. It has been estimated that the demand for proppants will be in the millions of tons and potentially billions of dollars, in order to fully develop all the Bakken\Three Forks reservoirs in the state. Currently, ultra-high quality natural sand proppants continue to be imported from locations across the globe including China, Russia, South America, and Canada, along with domestic sources in Minnesota, Wisconsin, Illinois, and Texas. Most recently, developing trends in the oil and gas industry have relaxed the initial desire for extreme-quality proppants. Throughout the industry the current trend is to use more cost-effective local sources with adequate proppant quality.

In order to address these rapidly changing proppant specifications, the North Dakota Geological Survey (Survey) is reevaluating North Dakota's sand resources for potential use as natural sand proppant. This report includes results of limited proppant characterization testing on 19 selected bedrock sandstones in south-central and western North Dakota (Figure 1). The Survey first evaluated North Dakota sands for proppant potential in 2010 (Anderson, 2011). Planned follow-on studies will include additional testing and characterization work similar in scope to that reported by Anderson (2011).

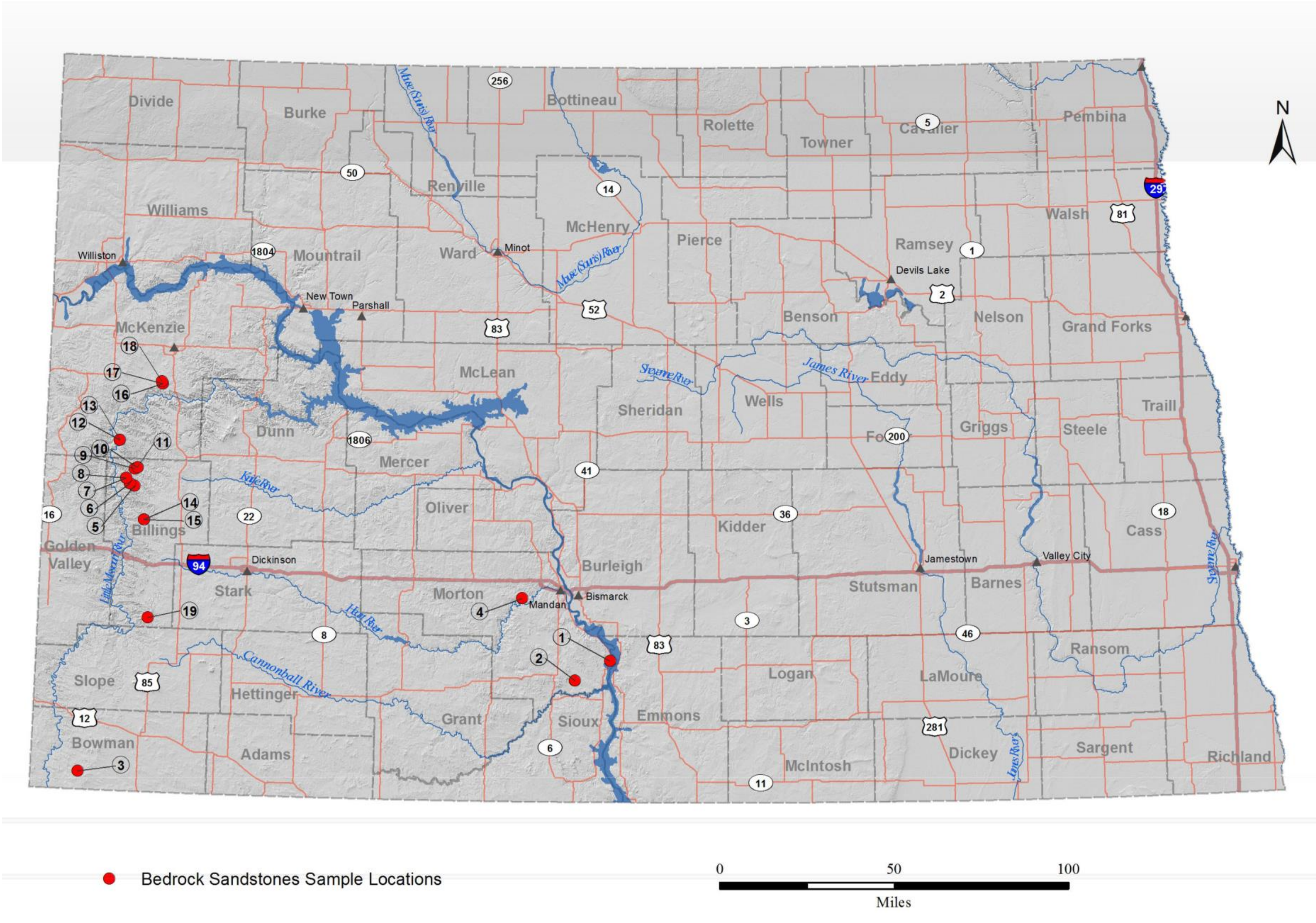


**Figure 1.** Location of selected bedrock sandstones sampled and tested for preliminary evaluation of use as natural sand proppant.

## BEDROCK SANDSTONE SAMPLE COLLECTION

### Description of Sample Collection

Samples of bedrock sandstone bedrock were obtained primarily from six stratigraphic units during this investigation. One sample was collected from each of the following: the Fox Hills, Hell Creek, and Cannonball Formations in Morton County, and the Ludlow Formation in Bowman County. Four were collected from the Bullion Creek Formation in Billings County. The majority of bedrock sandstone samples, 11, were collected from within the Sentinel Butte Formation in Billings and McKenzie Counties (Figure 2).

Samples of friable sandstones were collected by hand sampling with entrenching tools and shovels. Sandstones that were more heavily cemented were cored using a drill-powered auger bucket and further disaggregated by hand during sample collection and placed into sealed five-gallon buckets for transportation and lab shipment (Figure 3).

This initial, limited testing phase included gradational (sieve) analysis and photomicrography. The selection of samples was based on several factors including: known initial sand quality and character, proximity to oil and gas development in the Bakken/Three Forks in the Williston Basin of North Dakota, and the geological origin and areal extent of the sampled deposits (Plate III).

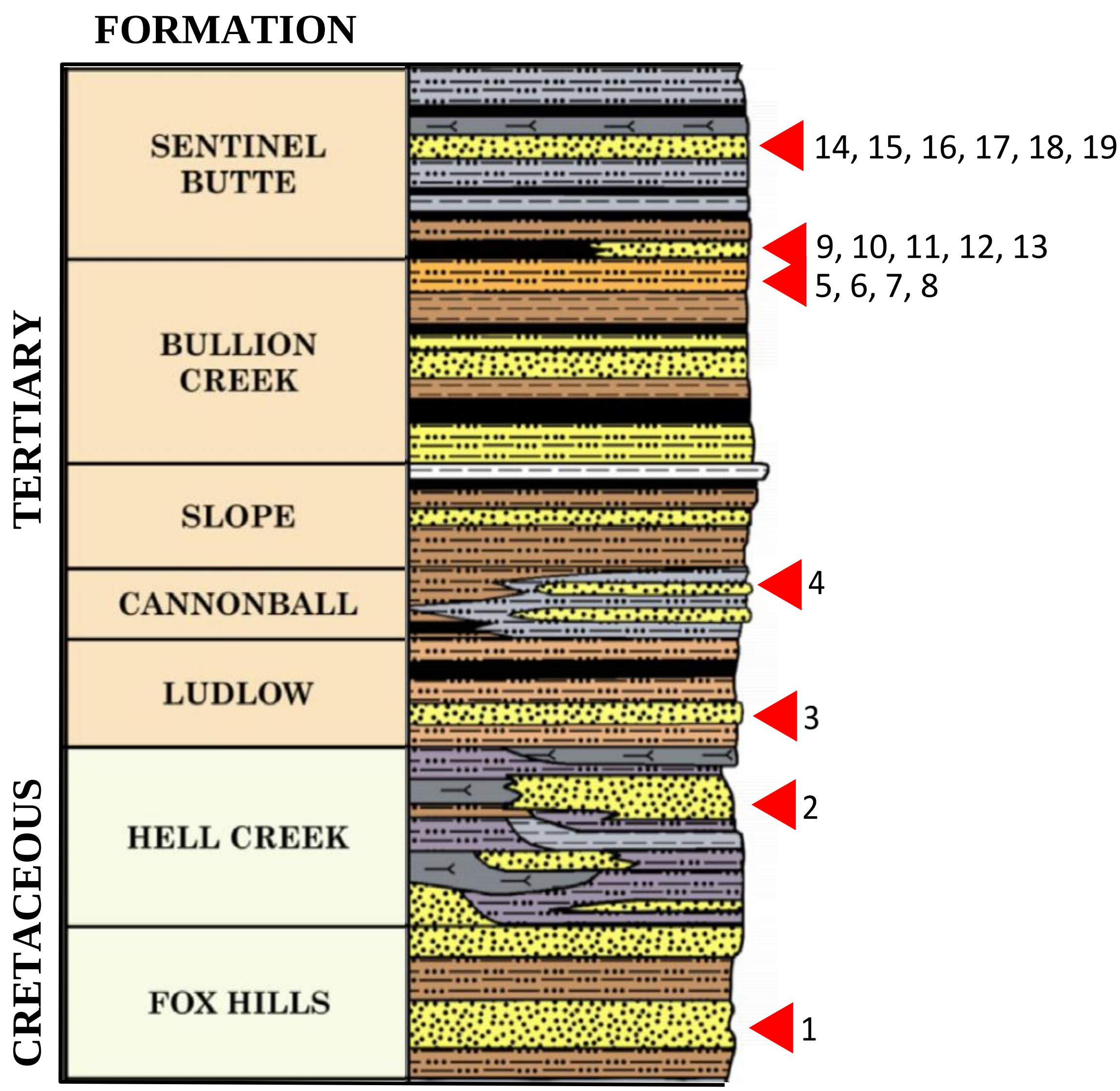


**Figure 2.** The stratigraphic position of sandstone samples (Nos. 1-19) collected for this study. Stratigraphic column modified from Murphy and others (2009).

**Figure 3.** Bedrock sandstone sample collection on an outcrop of Sentinel Butte Formation using a battery-operated hammer drill. Using this portable coring device permits sampling below the weathered zone of the outcrop, providing a better representative sample of the sandstone for testing and characterization. The custom fabricated three-inch diameter coring barrel permits rapid collection in semi-cemented rocks.

## Fox Hills Formation Sandstone

The Fox Hills Formation consists of marine to brackish-water deposits of Late Cretaceous age (Carlson, 1983) and is predominantly exposed in south-central and southwestern North Dakota (Plate III). The Fox Hills Formation sandstones were deposited in marine off-shore and near-shore environments. The sandstone members of the formation include the Colgate and Timber Lake Members which are both found in southeastern Morton County (Figure 4).

**Figure 4.** View to the east of an outcrop of sandstone (Fox Hills Formation) in southeastern Morton County (T. 135 N., R. 79 W., Sec. 2., SW ¼). Sample No. 1 was collected from the base (denoted by the arrow) of this massive, poorly cemented sandstone outcrop at this location.

## Sample No. 1

A yellow-brown sandstone approximately 15 feet thick at outcrop occurs in southeastern Morton County adjacent to N.D. Hwy 1806. This sandstone is poorly cemented and comprised of well-sorted, fine-grained sand. The sample was collected at two feet above the base of the exposure and no internal grading was noted. This sample exhibited no reaction to dilute (10%) hydrochloric acid. The grains are comprised primarily of quartz, feldspar, and lithic clasts (Sample No. 1, Plate I).

## Hell Creek Formation Sandstone

Sandstones of the Hell Creek Formation can be found in badlands topography in southeastern Morton County as well as the Little Missouri in southwestern Slope and western Bowman Counties. Sandstones within the formation are primarily non-marine, and were deposited in flood-plain environments near the margins of Late Cretaceous seas (Carlson, 1983). Sandstone lithology is laterally variable and can be poorly to well cemented at outcrop (Figure 5).

**Figure 5.** View to the southeast of a weathered outcrop of Hell Creek Formation sandstone in southeastern Morton County (T. 134 N., R. 80 W., Sec. 6., SW ¼). Sample No. 2 (arrow) was collected from the light-gray, massive, well cemented sandstone at 2.5-ft below land surface.

## Sample No. 2

In southeastern Morton County a relatively thin (5-ft), discontinuous bed of sandstone can be found outcropping within badlands terrain. This sandstone is light-gray to brown, fine-grained and exhibits little to no overall grading at the outcrop. Sample No. 2 was collected within the upper, well-cemented zone and exhibited no reaction to dilute HCl. This sand is composed of predominantly quartz and feldspar, with accompanying amounts of lithic rock fragments (Sample No. 2, Plate I).

### Ludlow Formation Sandstone

The Ludlow Formation contains channel sandstones as thick as 100 feet that may be laterally continuous for several miles in far southwestern North Dakota. Extensive outcrops occur along the Little Missouri Badlands in southwestern Slope and Bowman counties (Figure 6) and along the Cannonball River in south-central North Dakota. The Ludlow (Paleocene) was deposited in the channel, near-channel, and floodplains environments of low-gradient streams.

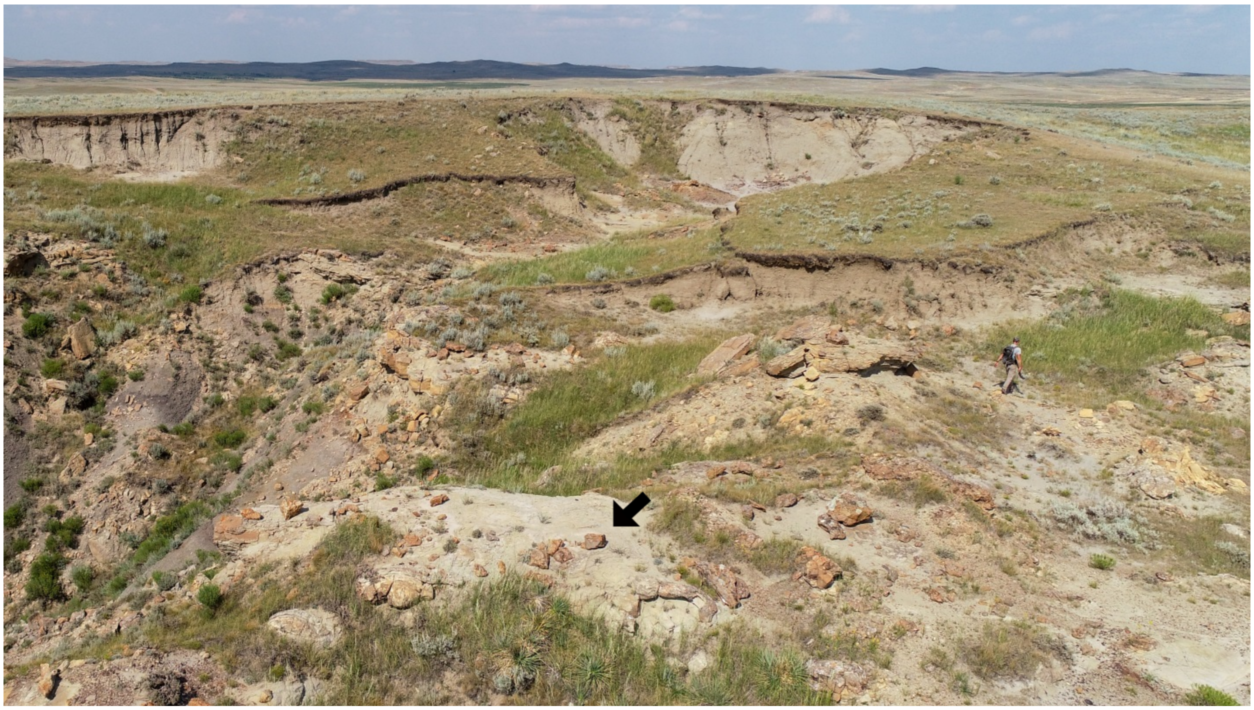

**Figure 6.** View to the northeast of an outcrop of Ludlow Formation sandstone overlying mudstone at Mud Buttes in southwestern Bowman County (T. 129 N., R. 105 W., Sec. 1., SW ¼). Sample No. 3 (arrow) was collected from the base of a weakly-bedded sandstone just west of this location.

### Sample No. 3

A sandstone, 25 feet thick occurs near the base of the Ludlow Formation in southwestern Bowman County. This unit is poorly cemented and comprised of well-sorted, fine-grained sand. The sample was collected one foot above the base of the unit, and no grading was observed. The sample exhibited no reaction to dilute HCl and the grain composition includes significant fractions of quartz, feldspar, and lithic clasts (Sample No. 3, Plate I).

**Cannonball Formation Sandstone**

Sandstones of the Cannonball Formation are found predominantly across Burleigh, Morton, Grant, and Adams Counties, along with more isolated outcrops in Bowman and Slope Counties. Cannonball sandstones tend to be interbedded with mudstones and siltstone, medium to fine-grained, and moderately to well-cemented (Figure 7).

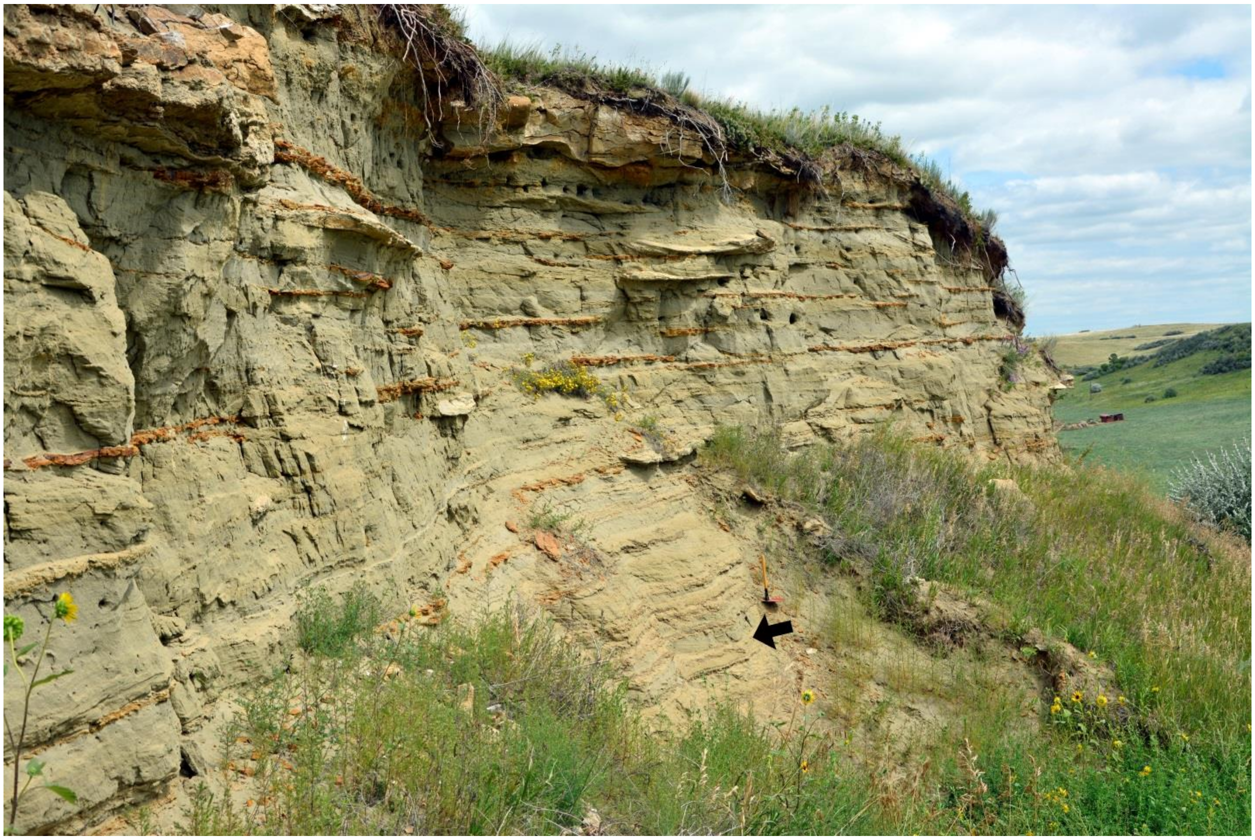

**Figure 7.** View to the east of an outcrop of Cannonball Formation sandstone in eastern Morton County (T. 138 N., R. 83 W., Sec. 2., SE ¼). Sample No. 4 (arrow) was collected from this bedded sandstones.

**Sample No. 4**

In eastern Morton County over 200 feet of the Cannonball formation is exposed along the Heart River (Cvancara, 1976). This sandstone was sampled on an interbedded outcrop and is moderately to well-cemented and consists of medium to fine-grained, well-sorted sand. Grains are composed predominantly of quartz and feldspar, with variable amounts of lithic rock fragments (Sample No. 4, Plate I). Sandstones within the Cannonball Formation tend to be cross-bedded, contain significant amounts of concretions and concretionary bedforms, and trace fossils such as *ophiomorpha*. The sample collected from this outcrop exhibited a very slight reaction to dilute HCl.

## Bullion Creek Formation Sandstones

Channel sandstones in the Bullion Creek Formation are present at or near the surface over several large areas in southwestern North Dakota, most notably in extensive outcrops along the Little Missouri Badlands in southern McKenzie, Billings (Figures 8 & 9), Golden Valley, and northern Slope counties. These fine-grained sandstones were deposited in low-energy fluvial systems during the Paleocene. Individual sand bodies can be up to 75 feet in thickness locally and laterally continuous over several miles. Variable amounts of secondary carbonate were observed, but overall, Bullion Creek sandstones are poorly cemented and contain relatively few concretions. Reactive carbonate concentrations as reported by Royse (1967) across the entire stratigraphic interval of the formation, ranged dominantly from 0 to 32%. Grains are typically subangular and composed of 32-68% quartz, 2-16% feldspar, and 26-53% lithic clasts (Steiner, 1978).

**Figure 8.** View to the northeast of an outcrop of upper Bullion Creek Formation sandstone in northern Billings County (T. 143 N., R. 101 W., Sec. 16., NW ¼). Sample Nos. 5 (lower arrow) and 6 (upper arrow) were collected from the middle portions of this sandstone.

### Samples No. 5-6

Samples were obtained from a bed of sandstone 55 feet thick near the top of the Bullion Creek Formation. In northwestern Billings County the unit is fine-grained, moderately cemented, and well sorted, and exhibits little to no overall grading. Sample No. 5 was collected 20 feet above the base of the channel, and Sample No. 6 was collected 26 feet above the channel base. Both samples exhibited very slight field acid reactivity. Both sands are composed of predominantly quartz and feldspar, with lesser amounts of lithic rock fragments dominated by chert (Sample Nos. 5 & 6, Plate I).

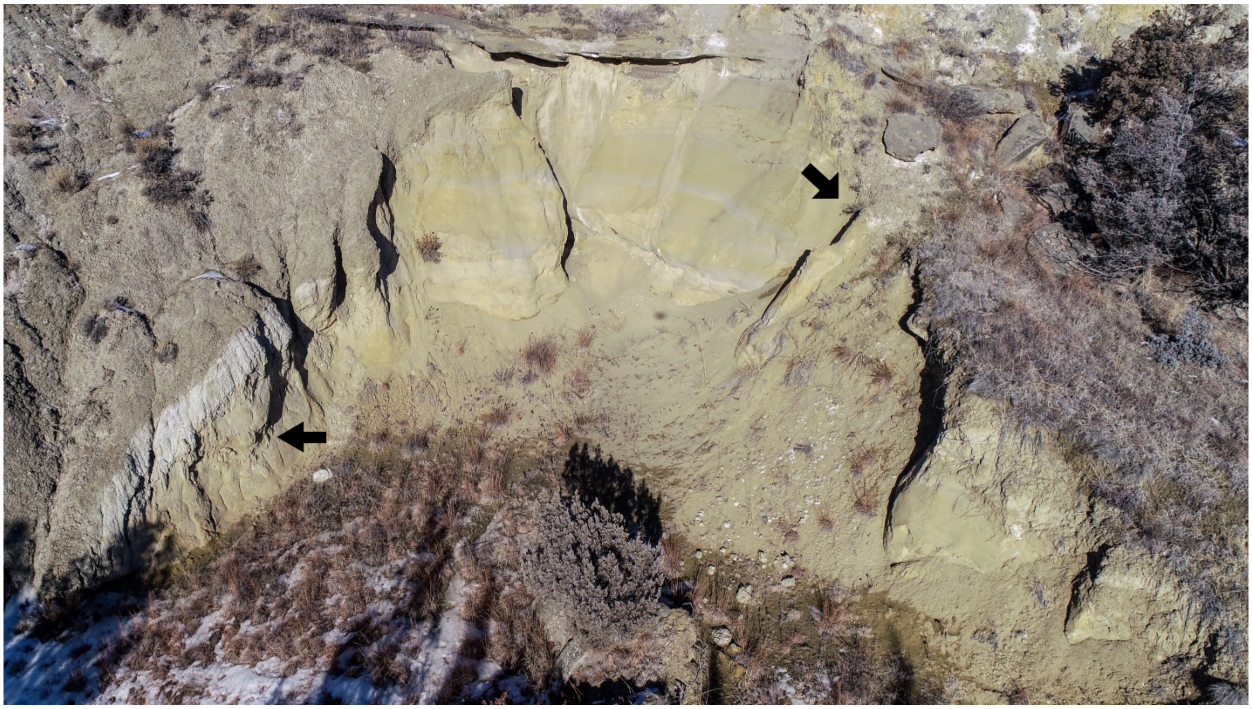

**Figure 9.** View to the north of an outcrop of upper Bullion Creek Formation sandstone in northern Billings County (T. 144 N., R. 102 W., Sec. 36., SE ¼). Sample No. 7 was collected from the base of this weakly-bedded sandstone just west of this location, and Sample No. 8 (arrow) was collected near the top of this sandstone at the left of this photo.

**Samples No. 7-8**

Samples were obtained from a 45-foot-thick sandstone in northwestern Billings County in the uppermost portion of the Bullion Creek Formation. The sandstone is poorly to moderately cemented and well to very well-sorted. The samples exhibit weak normal grading from fine-grained (Sample No. 7, collected eight feet above the base of the channel) to very fine-grained (Sample No. 8, collected 40 feet above the base of the channel) sand. Field acid reactivity ranged from slightly (Sample No. 7) to strongly reactive (Sample No. 8). Grains are predominantly of quartz and feldspar, with variable minor amounts of lithic rock fragments dominated by chert (Samples Nos., 7 & 8, Plate I). This sand is the stratigraphic equivalent of Samples No. 5 and 6, which were sampled approximately three miles to the southeast.

## Sentinel Butte Formation Sandstones

The Sentinel Butte Formation is present at the surface over much of southwestern North Dakota. Channel sandstones up to 100 feet in thickness are observed in extensive outcrops throughout the Little Missouri Badlands in eastern Billings, McKenzie, and northern Dunn counties (Figure 10). These rocks, late Paleocene in age, were deposited in similar settings to those of the underlying Bullion Creek Formation. Some major sand bodies, such as the "basal sand" (Sample No. 9-13) are laterally continuous across multiple townships and were recognized by previous workers (Royse, 1967) as silty, cross-bedded, fine sand, ranging in the thickness from tens of feet to over 100 feet. Sandstone cementation ranges widely from very poor to moderate. Secondary carbonate levels are similarly variable, but reported by previous workers at around 6%, tending to decrease from the southwest to the northeast (Royse, 1967). Concretions may be locally abundant. Grains are typically subangular and composed of 20-62% quartz, 8-43% feldspar, and 18-54% lithic clasts (Steiner, 1978). Sandstones within the Sentinel Butte Formation classify petrologically as Litharenites to Felspathic Litharenites with clay contents consisting dominantly of authigenic Montmorillonite (Forsman, 1985).

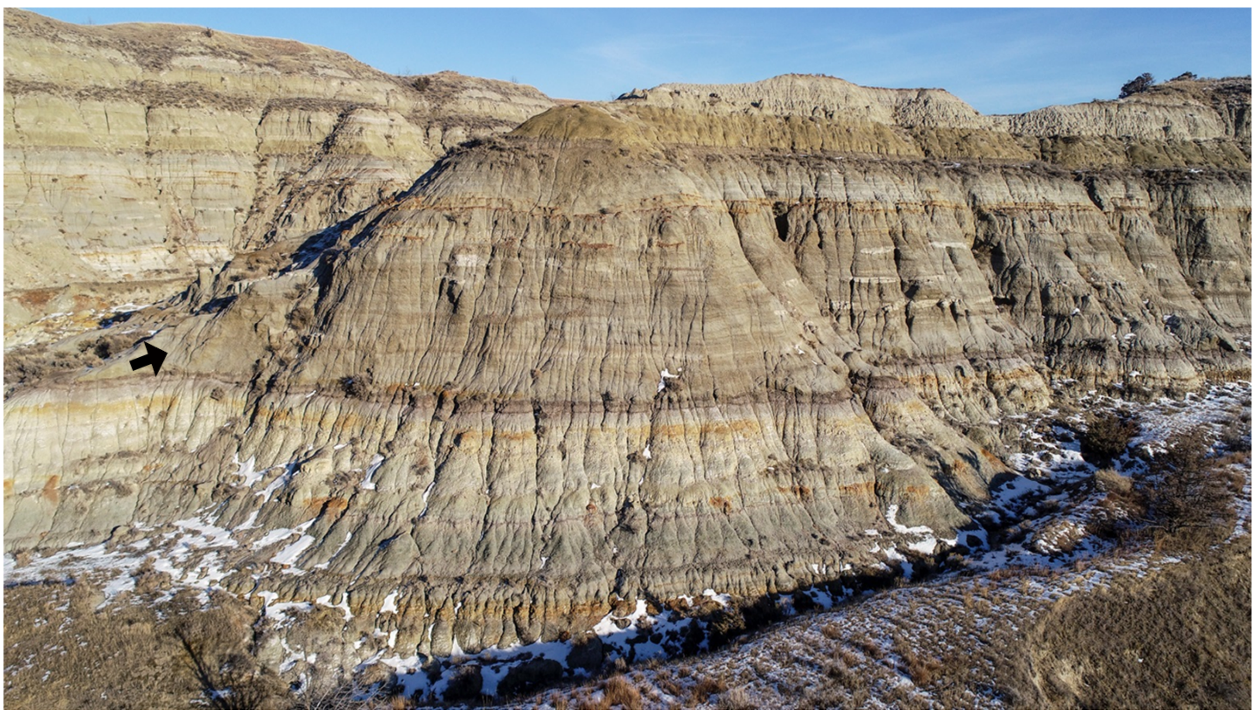

**Figure 10.** View to the east of an outcrop of sandstone at the base of the Sentinel Butte Formation in northern Billings County (T. 144 N., R. 101 W., Sec. 16., SW ¼). At this locality, the sandstone is bound by two thin carbonaceous mudstones (dark beds) and exhibits characteristic trough-shaped cross- stratification. Sample No. 9 (arrow) was sampled near the base of this unit at the center left of the photo.

**Sample No. 9**

The “basal sand” of the Sentinel Butte Formation is well-exposed in northwestern Billings County (Figure 11). Here the sandstone is approximately 30 feet thick, fine-grained, contains minor components of silt and clay, and grades to silt in the upper two feet. Minor normal grading may be present at small scales within individual trough cross-beds. The sample was collected two feet above the base of the unit.

Where sampled, the sandstone exhibited a very slight reaction to HCl. Grain composition is predominantly quartz and feldspar, with lesser amounts of lithic clasts (Sample No. 9, Plate I).

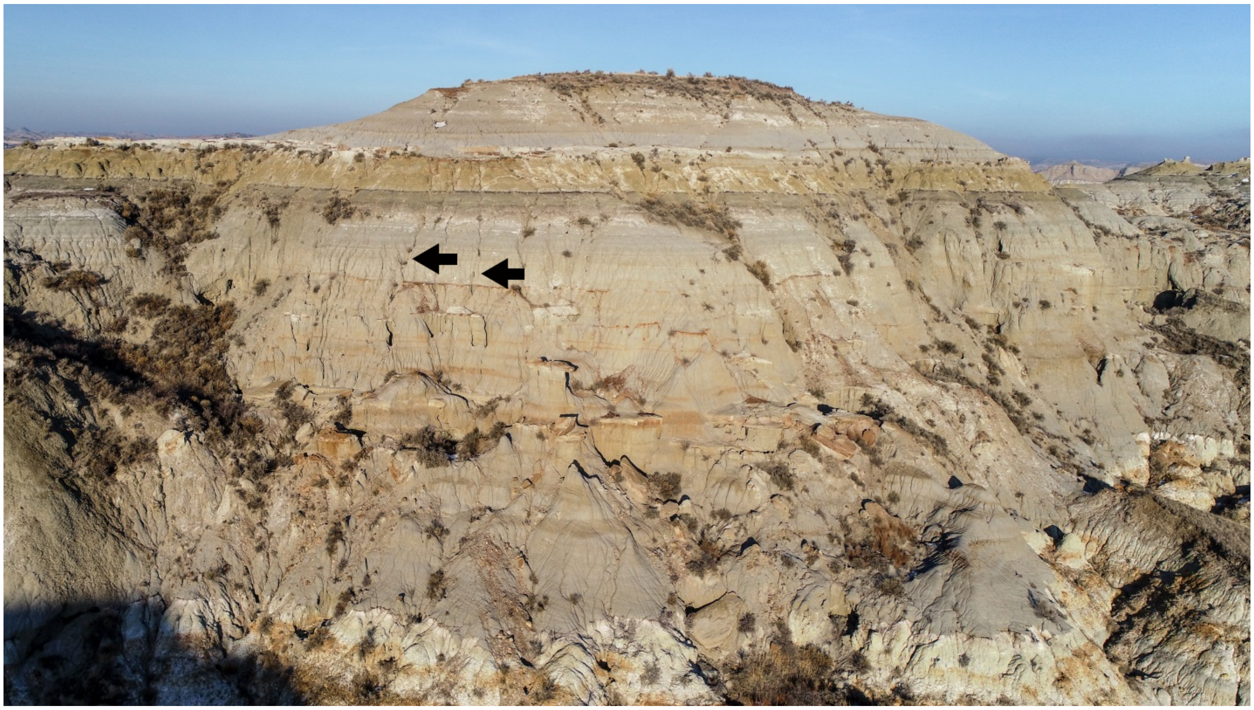

**Figure 11.** View to the northeast of an outcrop of sandstone at the base of the Sentinel Butte Formation in northern Billings County (T. 144 N., R. 101 W., Sec. 16., NE ¼). Samples No. 10 (lower arrow) and 11 (upper arrow) were collected from an individual trough cross-bed near the top of this unit.

**Samples No. 10-11**

Less than a mile to the northeast of Sample No. 9, the “basal sand” of the Sentinel Butte is 35 feet thick. Sample No. 10 was collected 31 feet above the base of the sandstone and Sample No. 11 was collected 33 feet above the base. The upper portions of this sandstone are similarly fine-grained with a minor component of silt. Localized weak grading is present within individual trough cross-beds. Neither sample exhibited reactivity to HCl. Lithic clasts are proportionally higher in these samples, but quartz and feldspar are still the predominant clasts (Sample Nos. 10 & 11, Plate I).

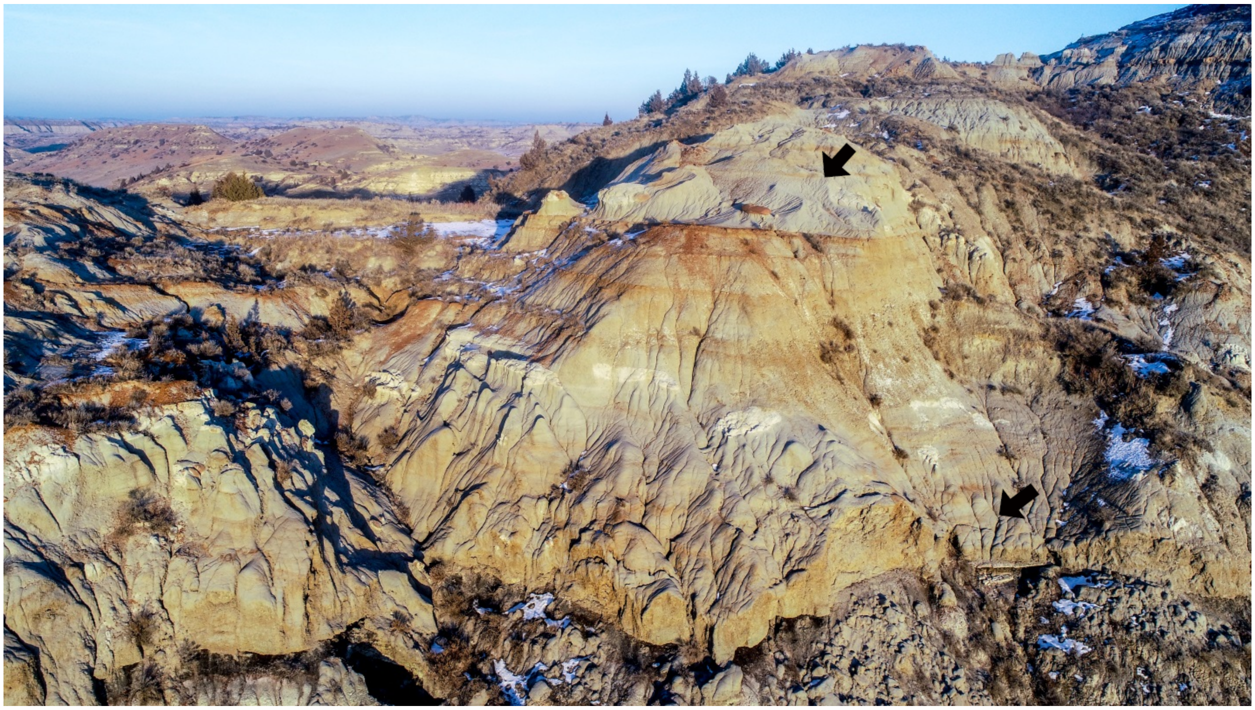

**Figure 12.** View to the northeast of an outcrop of sandstone at the base of the Sentinel Butte Formation in southern McKenzie County (T. 145 N., R. 101 W., Sec. 6., SE ¼). Sample No. 12 (lower arrow) was taken near the base of this sandstone (lower right of the photo), and Sample No. 13 (upper arrow) was obtained from the light gray, cross-bedded sandstone in the upper middle of the photograph.

**Samples No. 12-13**

The "basal sand" of the Sentinel Butte Formation is 36 feet thick where it was sampled in southern McKenzie County (Figure 12). Sample No. 12 was collected five feet above the base of the bed, and Sample No. 13 was collected 30 feet from the base. The sandstone is fine grained and moderately sorted, with a small component (5%) of silt throughout. No overall grading was apparent in the bed, but minor normal grading occurs within cross-beds. Neither sample exhibited reactivity to HCl. Carbonaceous stringers were present near the base of the bed, represented by carbonaceous grains in Sample No. 12. Rock fragments represent an appreciable percentage of the grains in all samples from the "basal sand" of the Sentinel Butte, approaching the percentages of quartz and feldspar in some samples (Sample Nos. 12 & 13, Plate I).

**Figure 13.** View to the northeast of an outcrop of sandstone from Sentinel Butte Formation in northern Billings County (T. 142 N., R. 101 W., Sec. 36., NW ¼). Sample No. 14 (lower arrow) was collected near the base of this sandstone (at the lower left of the photo), and Sample No. 15 (upper arrow) was collected from the upper portion of the bed just below the thin lignite.

**Samples No. 14-15**

Thick sandstones are present in the lower to middle portions of the Sentinel Butte Formation in north-central Billings County (Figure 13). Where sampled, this sandstone was poorly cemented and 50 feet thick. Sample No. 14 was collected three feet above the base of the sandstone, and Sample No. 15 was collected 47 feet above the base. The bed exhibits occasional normal grading from fine- to very fine- grained sandstone. Field acid reactivity varied from slightly reactive (Sample No. 14) to non-reactive (Sample No. 15). Lithic clasts represent a large component of these samples, but less so in the finer- grained Sample No. 15, which is predominantly quartz and feldspar (Sample Nos. 14 & 15, Plate I).

**Figure 14.** View to the southeast of an outcrop of Sentinel Butte Formation sandstone in central McKenzie County (T. 148 N., R. 99 W., Sec. 18., NW ¼). Sample No. 16 (arrow) was collected from the light gray sandstone at the base of the outcrop.

**Sample No. 16**

Sample 16 was collected five feet from the top of a 25-foot-thick sandstone in the lower Sentinel Butte Formation in central McKenzie County (Figure 14). This sand is moderately-sorted and fine-grained with a visible fraction of silt and clay. This sandstone was moderately well-consolidated and did not react to HCl where sampled. No grading was observed. Lithic clasts represent an appreciable percentage the grains in all samples from the basal sand of the Sentinel Butte, approaching the fractions of quartz and feldspar in this sample.

**Figure 15.** View to the west of an outcrop of weakly bedded sandstone in the Sentinel Butte Formation in central McKenzie County (T. 148 N., R. 99 W., Sec. 18., NW ¼). Sample No. 17 (arrow) was collected just above the concretionary zone in the light gray sandstone.

**Sample No. 17**

A second sandstone, separated by 30 feet of mudstone, occurs just above the Sample No. 16 sandstone in the lower-middle portions of the Sentinel Butte Formation in central McKenzie County (Figure 15). This sandstone is 15 feet thick, well sorted, and very fine-grained. Sample No. 17, collected 10 feet above the base of the sandstone contains more than 10% silt by weight. This bed did not exhibit grading in the field and reacted strongly to HCl. The sandstone was well-cemented relative to other samples in this study, and contained a moderate abundance of concretions. There are proportionally fewer lithic clasts observable in this sandstone, which is predominantly quartz and feldspar (Sample No. 17, Plate I).

**Figure 16.** View to the north of an outcrop of weakly-bedded Sentinel Butte Formation sandstone in central McKenzie County (T. 148 N., R. 99 W., Sec. 7., NW ¼). Sample No. 18 (arrow) was collected just above the base of the outcrop at the right of the photo. The concretionary zones in this weakly-bedded sandstone are present throughout the outcrop.

**Sample No. 18**

The 15-foot-thick sandstone is laterally continuous over a one mile distance to the northwest in central McKenzie County where it was again sampled 10 feet above its base in the lower- middle portion of the Sentinel Butte Formation (Figure 16). At this locality the sandstone is 35 feet thick, well cemented and very well sorted, but was fine grained with a lower silt fraction. Lenticular iron concretions are common within this sandstone at this locality and it also reacted strongly to dilute HCl. Quartz and feldspar are the dominant mineral grains, with relatively fewer lithic clasts present (Sample No. 18, Plate I).

**Figure 17.** Satellite imagery (Copernicus, 2017) of an outcrop of weakly bedded sandstone in the Sentinel Butte Formation in southern Billings County (T. 137 N., R. 101 W., Sec. 16., SE ¼). View is to the north. Sample No. 19 (arrow) was collected from the thick sandstone exposed along the western rim of the Kendley Plateau.

**Sample No. 19**

Sandstone from the middle part of the Sentinel Butte Formation is exposed in southern Billings County (Figure 17). This sandstone, 60 feet thick, was sampled 20 feet above its base. It is moderately sorted, very poorly cemented, and fine- to medium-grained. Where sampled, it exhibited a very slight reaction to dilute HCl. Lithic clasts are the predominant grains, consistent with the overall trend for the coarser Bullion Creek and Sentinel Butte sandstones to have lower fractions of quartz (Sample No. 19, Plate I).

## DESCRIPTON OF TESTING AND RESULTS

Sandstone samples 1 – 19 (Table 1) were submitted for preliminary testing and characterization by gradational (sieve) analysis and comparative photomicrography. Testing was done in accordance with published and industry approved recommendations and specifications. Sieve analyses were completed by Golder Associates in Houston, Texas.

### Sample Preparation

All samples were oven dried to a constant temperature of 230 F$^{o}$ and prepared using dry sieve analysis methods. Samples were sieved across 24 standard sieves ranging from the No. 10 to No. 400 (Table 2).

### Particle Size Distribution – Textural (Sieve Analysis)

Sieve analyses are conducted on sandstone samples in order to characterize the quantities of different sized sand grains within a sample. A series of stacked, wire-mesh sieves of standard sizes, are used to sieve each sand sample. The amounts of sand, either being retained by the screen on each successively smaller sized sieve opening (% retained) or passing through the screen (% passing), are recorded. The results are typically reported as tabular data (Table 2) or in graphical form on a grain-size distribution diagram (Plate 2). The resulting graphs and grain-size curves convey information on the quantities of particle sizes present and the degree of sorting or the variability of grains sizes. A well sorted sample (poorly graded in engineering parlance), will have much of the sample volume at or near the same size classes (Table 2), resulting in a very steep curve on the grain size distribution diagram (Plate II). All of the samples selected for testing were well sorted (poorly graded) sandstones. Conversely, a poorly sorted (well-graded) sample will have small amounts of grains of many different sizes which will result in a grain-size distribution diagram with a more flat or gradual curve.

There are several slightly different types of sediment classification schemes, most notably, Modified Wentworth, Unified Soil Classification System (USCS), American Association of State Highway and Transportation Officials (AASHTO), and several others. Generally these classifications vary in where they draw boundaries between two different types of sediment (e.g. sand and gravel). For the purposes of sedimentological characterization in this report, the USCS system is used for presentation of the grain-size distribution data. In addition some calculated summary engineering values are also presented.

All of the sandstone samples tested fell into the grain size ranges for classification as a “Sand”. These sands can be further characterized as well sorted (poorly graded) to very well sorted, medium grained sands. Sample Nos. 1-4, 9-13, 16 & 19 all had their most abundant sand quantities in the 40/70 size range, whereas Sample Nos. 5-7, 14 & 15, and 17 & 18 all had their most abundant sand concentrations in the 70/140 size range. Sample No. 8 consisted of very small grain sizes dominantly in the very fine sand to silt size range (i.e. % retained on the #200 sieve) (Table 3).

**Table 1.** Location of Selected Bedrock Sandstone Samples

| Sample | Date | Stratigraphic Unit | County | Location (T.R.S.Q.) |
|---|---|---|---|---|
| 1 | 6/21/2018 | Fox Hills Formation | Morton | 135-79-2-SW |
| 2 | 6/21/2018 | Hell Creek Formation | Morton | 134-80-6-SW |
| 3 | 5/21/2018 | Ludlow Formation | Bowman | 129-105-1-SW |
| 4 | 6/21/2018 | Cannonball Formation | Morton | 138-83-2-SE |
| 5 | 5/23/2018 | Bullion Creek Formation | Billings | 143-101-16-NW |
| 6 | 5/23/2018 | Bullion Creek Formation | Billings | 143-101-16-NW |
| 7 | 5/14/2018 | Bullion Creek Formation | Billings | 144-102-36-SE |
| 8 | 5/14/2018 | Bullion Creek Formation | Billings | 144-102-36-SE |
| 9 | 5/9/2018 | Sentinel Butte Formation, basal sand | Billings | 144-101-16-SW |
| 10 | 6/19/2018 | Sentinel Butte Formation, basal sand | Billings | 144-101-16-NE |
| 11 | 6/19/2018 | Sentinel Butte Formation, basal sand | Billings | 144-101-16-NE |
| 12 | 5/9/2018 | Sentinel Butte Formation, basal sand | McKenzie | 145-101-6-SE |
| 13 | 5/9/2018 | Sentinel Butte Formation, basal sand | McKenzie | 145-101-6-SE |
| 14 | 5/9/2018 | Sentinel Butte Formation | Billings | 142-101-36-NW |
| 15 | 5/9/2018 | Sentinel Butte Formation | Billings | 142-101-36-NW |
| 16 | 6/7/2018 | Sentinel Butte Formation | McKenzie | 148-99-18-NW |
| 17 | 6/7/2018 | Sentinel Butte Formation | McKenzie | 148-99-18-NW |
| 18 | 6/7/2018 | Sentinel Butte Formation | McKenzie | 148-99-7-NW |
| 19 | 5/31/2018 | Sentinel Butte Formation | Billings | 137-101-16-SE |

T-R-S-Q = Township-Range-Section-Quarter

**Table 2.** Weight % Retained

| US Standard Sieve No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8* | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0.1 | 0.0 | 0.2 | 1.4 | 0.0 | 0.1 | 0.0 | 0.0 | 0.5 | 4.0 | 7.9 | 0.1 | 0.0 | 0.0 | 0.0 | 0.4 | 3.0 | 0.0 | 0.0 |
| 12 | 0.1 | 1.4 | 0.2 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 | 2.8 | 1.0 | 1.1 | 2.0 | 0.9 | 0.0 | 0.0 | 0.3 | 1.2 | 0.3 | 0.0 |
| 14 | 0.1 | 3.9 | 0.3 | 0.2 | 0.0 | 0.1 | 0.0 | 0.2 | 5.0 | 1.2 | 1.1 | 3.5 | 2.3 | 0.3 | 0.2 | 0.5 | 1.4 | 1.1 | 0.0 |
| 16 | 0.1 | 2.9 | 0.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.2 | 4.1 | 0.7 | 0.6 | 2.4 | 1.9 | 0.4 | 0.2 | 0.6 | 0.7 | 1.0 | 0.0 |
| 18 | 0.2 | 3.6 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.3 | 5.3 | 0.8 | 0.7 | 3.0 | 2.7 | 0.5 | 0.3 | 0.8 | 0.9 | 1.1 | 0.1 |
| 20 | 0.1 | 3.7 | 1.0 | 0.3 | 0.1 | 0.0 | 0.0 | 0.3 | 5.9 | 0.8 | 0.7 | 2.9 | 3.1 | 0.6 | 0.7 | 1.0 | 0.8 | 1.0 | 0.1 |
| 25 | 0.2 | 2.9 | 1.4 | 0.2 | 0.2 | 0.1 | 0.0 | 0.4 | 4.4 | 0.9 | 0.6 | 2.5 | 2.5 | 0.7 | 1.1 | 0.8 | 1.2 | 0.9 | 0.2 |
| 30 | 0.3 | 2.9 | 1.7 | 0.2 | 0.4 | 0.0 | 0.0 | 0.4 | 4.0 | 0.8 | 0.6 | 2.1 | 2.1 | 0.6 | 1.1 | 0.9 | 0.8 | 0.7 | 0.3 |
| 35 | 0.5 | 3.4 | 2.4 | 0.3 | 1.0 | 0.1 | 0.0 | 0.4 | 4.7 | 0.8 | 0.9 | 2.6 | 3.0 | 1.2 | 1.8 | 0.7 | 0.7 | 1.0 | 1.0 |
| 40 | 0.8 | 4.4 | 3.2 | 0.3 | 1.3 | 0.1 | 0.0 | 0.8 | 3.8 | 1.0 | 1.0 | 3.1 | 3.3 | 1.6 | 1.8 | 1.0 | 1.0 | 0.9 | 3.9 |
| 45 | 0.7 | 3.8 | 3.2 | 0.4 | 1.2 | 0.2 | 0.2 | 0.7 | 3.0 | 0.9 | 1.3 | 3.0 | 4.0 | 1.2 | 1.5 | 1.0 | 0.7 | 0.7 | 11.1 |
| 50 | 1.8 | 12.2 | 13.2 | 2.7 | 2.5 | 0.5 | 0.5 | 1.5 | 7.5 | 3.0 | 9.5 | 10.2 | 16.8 | 3.5 | 3.4 | 2.6 | 1.2 | 1.2 | 40.0 |
| 60 | 11.4 | 20.7 | 21.7 | 16.1 | 4.8 | 1.8 | 1.0 | 1.8 | 11.5 | 15.3 | 24.7 | 17.6 | 17.6 | 9.3 | 9.7 | 15.7 | 1.5 | 1.9 | 26.7 |
| 70 | 33.2 | 11.1 | 22.6 | 27.7 | 15.3 | 5.9 | 2.3 | 2.0 | 12.6 | 30.4 | 22.8 | 14.0 | 14.0 | 16.0 | 22.5 | 37.0 | 1.8 | 5.5 | 9.3 |
| 80 | 28.4 | 8.6 | 14.3 | 27.5 | 29.5 | 17.2 | 14.3 | 2.8 | 10.0 | 16.4 | 12.0 | 9.3 | 7.8 | 27.5 | 32.9 | 14.8 | 2.5 | 29.2 | 3.8 |
| 100 | 9.3 | 4.0 | 5.6 | 9.0 | 15.8 | 17.2 | 25.4 | 3.3 | 4.5 | 6.2 | 5.0 | 4.9 | 4.2 | 15.0 | 11.9 | 5.0 | 6.3 | 20.8 | 1.3 |
| 120 | 6.1 | 3.8 | 3.7 | 6.4 | 15.4 | 17.4 | 31.6 | 9.1 | 3.5 | 4.1 | 3.3 | 4.3 | 3.1 | 9.4 | 4.6 | 3.8 | 16.6 | 15.4 | 0.7 |
| 140 | 2.0 | 1.7 | 1.3 | 2.0 | 5.3 | 10.0 | 9.7 | 10.8 | 1.4 | 2.0 | 1.5 | 2.3 | 1.9 | 4.3 | 1.7 | 1.9 | 17.2 | 5.3 | 0.4 |
| 170 | 1.7 | 1.2 | 1.1 | 1.4 | 3.6 | 10.4 | 6.6 | 12.4 | 1.3 | 2.5 | 1.4 | 2.1 | 1.5 | 3.1 | 1.0 | 1.6 | 14.9 | 3.2 | 0.4 |
| 200 | 1.3 | 1.4 | 0.8 | 1.2 | 1.9 | 10.6 | 4.5 | 21.9 | 1.5 | 2.6 | 1.3 | 2.9 | 1.9 | 2.4 | 1.6 | 3.3 | 14.9 | 3.2 | 0.3 |
| 230 | 0.9 | 1.4 | 0.8 | 1.1 | 1.0 | 5.2 | 2.5 | 18.2 | 1.7 | 2.7 | 1.2 | 3.1 | 3.0 | 1.4 | 1.2 | 4.2 | 7.0 | 3.5 | 0.2 |
| 270 | 0.3 | 0.7 | 0.2 | 0.4 | 0.3 | 1.2 | 0.9 | 3.5 | 0.7 | 1.0 | 0.5 | 1.4 | 1.5 | 0.5 | 0.5 | 1.6 | 1.9 | 1.4 | 0.1 |
| 325 | 0.3 | 0.3 | 0.2 | 0.4 | 0.2 | 1.3 | 0.4 | 5.0 | 0.2 | 0.7 | 0.3 | 0.6 | 0.8 | 0.3 | 0.2 | 0.4 | 1.4 | 0.5 | 0.1 |
| 400 | 0.1 | 0.0 | 0.1 | 0.1 | 0.1 | 0.4 | 0.1 | 2.5 | 0.1 | 0.2 | 0.0 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.4 | 0.2 | 0.0 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 98.5 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

* 1.5% remaining on pan.

**Table 3.** Percent Sand In-Size Class

| Size Class | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/12 | 0.2 | 1.4 | 0.4 | 1.5 | 0.0 | 0.2 | 0.0 | 0.0 | 3.3 | 5.0 | 9.0 | 2.1 | 0.9 | 0.0 | 0.0 | 0.7 | 4.2 | 0.3 | 0.0 |
| 8/16 | 0.4 | 8.2 | 1.0 | 2.0 | 0.0 | 0.3 | 0.0 | 0.4 | 12.4 | 6.9 | 10.7 | 8.0 | 5.1 | 0.7 | 0.4 | 1.8 | 6.3 | 2.4 | 0.0 |
| 12/20 | 0.5 | 14.1 | 2.1 | 1.1 | 0.2 | 0.2 | 0.0 | 1.0 | 20.3 | 3.5 | 3.1 | 11.8 | 10.0 | 1.8 | 1.4 | 2.9 | 3.8 | 4.2 | 0.2 |
| 16/30 | 0.8 | 13.1 | 4.6 | 1.0 | 0.8 | 0.2 | 0.0 | 1.4 | 19.6 | 3.3 | 2.6 | 10.5 | 10.4 | 2.4 | 3.2 | 3.5 | 3.7 | 3.7 | 0.7 |
| 20/40 | 1.9 | 17.3 | 9.7 | 1.3 | 3.0 | 0.3 | 0.0 | 2.3 | 22.8 | 4.3 | 3.8 | 13.2 | 14.0 | 4.7 | 6.5 | 4.4 | 4.5 | 4.5 | 5.5 |
| 30/50 | 3.8 | 23.8 | 22.0 | 3.7 | 6.0 | 0.9 | 0.7 | 3.4 | 19.0 | 5.7 | 12.7 | 18.9 | 27.1 | 7.5 | 8.5 | 5.3 | 3.6 | 3.8 | 56.0 |
| 40/70 | 47.1 | 47.8 | 60.7 | 46.9 | 23.8 | 8.4 | 4.0 | 6.0 | 34.6 | 49.6 | 58.3 | 44.8 | 52.4 | 30.0 | 37.1 | 56.3 | 5.2 | 9.3 | 87.1 |
| 70/140 | 45.8 | 18.1 | 24.9 | 44.9 | 66.0 | 61.8 | 81.0 | 26.0 | 19.4 | 28.7 | 21.8 | 20.8 | 17.0 | 56.2 | 51.1 | 25.5 | 42.6 | 70.7 | 6.2 |

## Field Acid Reactivity

The amount of a particular sand that is soluble in strong acid is an important characteristic of an effective proppant, as acid treatments of oil and gas wells during completions are common in the hydraulic fracturing industry. API (1995a) recommends for sand used as proppant that no more than 2% (by weight) of 30/50 or larger-sized sand and no more than 3% (by weight) of 40/70 or smaller sized sand be soluble in a 12:3 hydrochloric (HCL) to hydrofluoric (HF) acid solution. An acid solubility analysis was beyond the scope of this initial phase of work. However, reactivity to dilute (10%) hydrochloric acid was noted during sample collection to serve as an indication of the carbonate reactivity of each sample. This consisted of a five-class effervescence assessment for each sample: 1) no reactivity (no reaction observed with the use of optics, 2) very slightly reactive (few bubbles seen), 3) slightly reactive (bubbles readily seen), 4) strongly reactive (bubbles quickly form low foam) or 5) violently reactive (thick foam forms immediately). More than half of the samples exhibited a visual reaction to HCL in the field, three of which reacted strongly. These results are suggestive of the presence of primary or secondary (matrix) carbonates in the sandstones, occasionally in significant amounts. Carbonate presence may be highly localized within the sandstones.

## Engineering Properties

Additional engineering properties can also be determined on data generated in a grain-size distribution diagram. This data can be used to quantitatively compare individual samples for potential engineering applications. For civil engineering applications, the effective size (D10) is the grain-size diameter corresponding to 10% finer on the sieve curve which can be related to many geotechnical soil properties. The uniformity coefficient (Cu) is the degree of similarity in grain sizes within the sample and is analogous to sorting. The lower the Cu number, the more well sorted (closer to uniformity) a sample is. The coefficient of gradation (Cc) indicates the spread of grain sizes across the sample and is also inversely analogous to sorting. In this case the higher the number, the greater the degree of gradation within the sample, i.e., its tendency towards a larger spread of grain sizes within the sample. Generally speaking, a well-graded sample is *poorly sorted* and a poorly graded sample is *well sorted*. The mean grain-size diameter is commonly used to characterize proppant distribution in hydraulic fracturing applications and the median grain-size diameter is used to characterize gravel-packing distributions (Table 4).

## Photomicrography

Splits from each sample were digitally photographed at 25x magnification using a Wild Heerbrugg M8 binocular microscope with an attached Olympus D72 camera. The camera uses the Olympus Steam Essentials (v.1.6.1) digital microscopy imaging software. Multiple images were taken for each sample at different focal resolutions and combined into depth-of-field composite photomicrographs (Plate I) to enable a detailed comparison of sand grain morphology and mineralogical composition.

**Table 4.** Summary of Gradational Analysis Engineering Properties

| NDGS No. | $D_{100}$ | $D_{60}$ | $D_{30}$ | Effective Size ($D_{10}$) | Uniformity Coefficient ($C_u$) | Coefficient of Gradation ($C_c$) | ISO Mean Diameter (mm) | Median Diameter (mm) |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.00 | 0.222 | 0.189 | 0.138 | 1.61 | 1.17 | 0.222 | 0.220 |
| 2 | 2.00 | 0.322 | 0.235 | 0.147 | 2.19 | 1.17 | 0.449 | 0.280 |
| 3 | 2.00 | 0.270 | 0.215 | 0.159 | 1.70 | 1.08 | 0.294 | 0.250 |
| 4 | 2.00 | 0.226 | 0.189 | 0.138 | 1.64 | 1.15 | 0.253 | 0.220 |
| 5 | 1.40 | 0.197 | 0.154 | 0.116 | 1.70 | 1.04 | 0.197 | 0.180 |
| 6 | 2.00 | 0.156 | 0.108 | 0.078 | 2.00 | 0.96 | 0.153 | 0.150 |
| 7 | 0.50 | 0.154 | 0.129 | 0.094 | 1.64 | 1.15 | 0.152 | 0.160 |
| 8 | 1.70 | 0.099 | 0.075 | 0.056 | 1.77 | 1.01 | 0.126 | 0.085 |
| 9 | 2.00 | 0.434 | 0.227 | 0.147 | 2.95 | 0.81 | 0.543 | 0.310 |
| 10 | 2.00 | 0.238 | 0.195 | 0.109 | 2.18 | 1.47 | 0.354 | 0.230 |
| 11 | 9.50 | 0.271 | 0.217 | 0.153 | 1.77 | 1.14 | 0.448 | 0.260 |
| 12 | 2.00 | 0.292 | 0.208 | 0.104 | 2.81 | 1.42 | 0.413 | 0.260 |
| 13 | 2.00 | 0.308 | 0.223 | 0.117 | 2.63 | 1.38 | 0.385 | 0.280 |
| 14 | 1.70 | 0.207 | 0.166 | 0.115 | 1.80 | 1.16 | 0.226 | 0.190 |
| 15 | 1.70 | 0.219 | 0.187 | 0.145 | 1.51 | 1.10 | 0.240 | 0.210 |
| 16 | 2.00 | 0.235 | 0.197 | 0.094 | 2.50 | 1.76 | 0.262 | 0.230 |
| 17 | 2.00 | 0.128 | 0.094 | 0.074 | 1.73 | 0.93 | 0.268 | 0.130 |
| 18 | 2.00 | 0.187 | 0.145 | 0.096 | 1.95 | 1.17 | 0.232 | 0.180 |
| 19 | 1.18 | 0.322 | 0.274 | 0.223 | 1.44 | 1.05 | 0.308 | 0.310 |

## SUMMARY

Selected North Dakota sandstones were sampled and tested for potential use as natural sand proppants in the hydraulic fracturing of oil and gas wells in the Williston Basin. Limited materials testing and sediment characterization, consisting of gradational analysis and photomicrography, indicated that these sandstones are medium to very-fine grained, consist of mixed mineralogy, and are generally texturally and mineralogically immature in comparison to high-quality “Ottawa White” type sands. It is likely that additional processing and material refinement steps will still be required to raise deposits of marginal quality up to applicable high-quality standards and specifications.

The recent oil and gas industry trend towards a relaxation of the need for ultra- high-quality natural sand proppants in lieu of local or regional natural sand proppant sources has led to the re-evaluation of North Dakota’s abundant sand deposits. The viability of North Dakota sand and sandstones may be made possible through deposit refinement during initial extraction and production. This would likely result in significant volume losses or through other material enhancement processes (such as resin coating or blending with ceramic proppants). The preliminary information contained in this report will also be beneficial in the continued characterization of North Dakota’s sand resources for use in other industrial sand applications.

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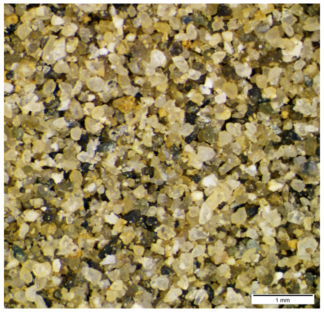
**Plate I.** Photomicrographs (25x) of selected bedrock sandstones in North Dakota.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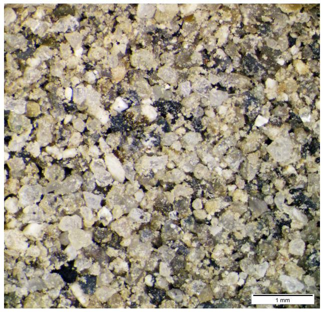
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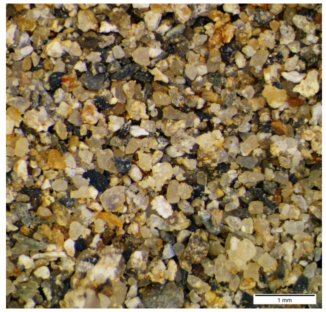
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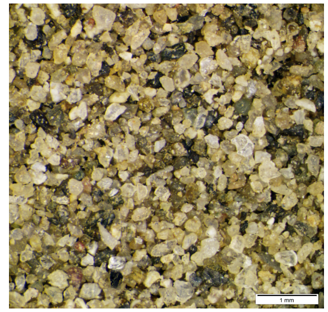
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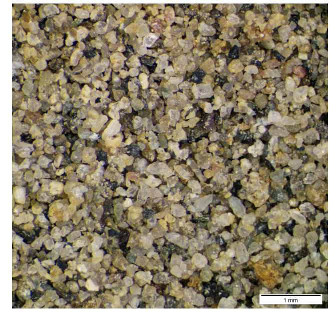
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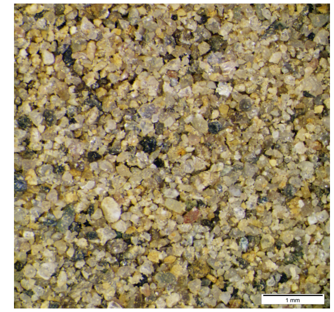
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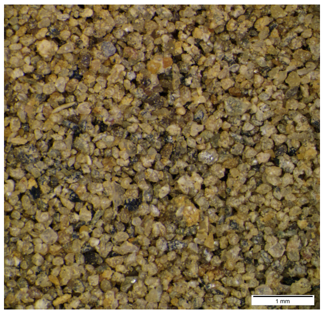
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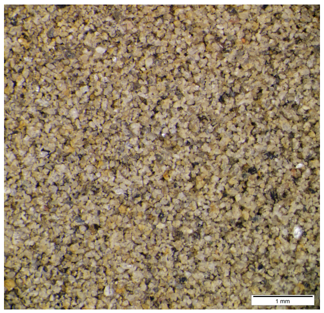
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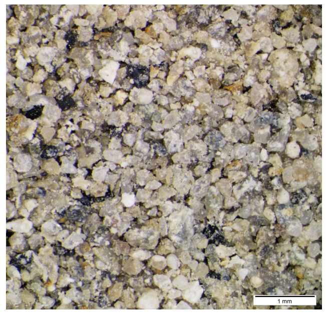
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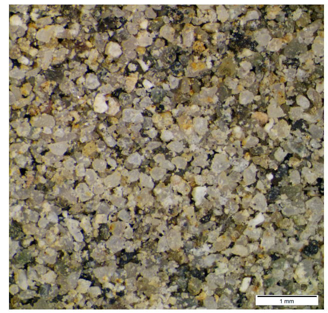
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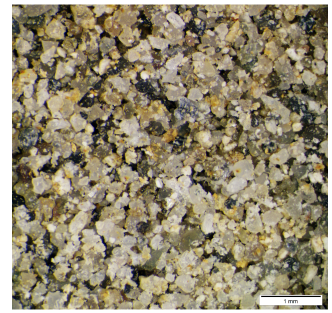
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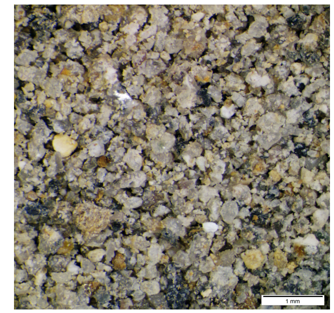
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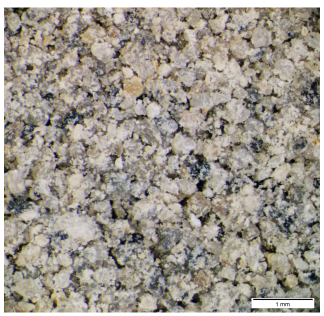
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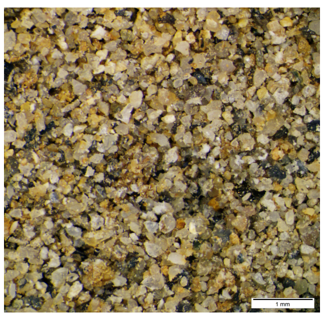
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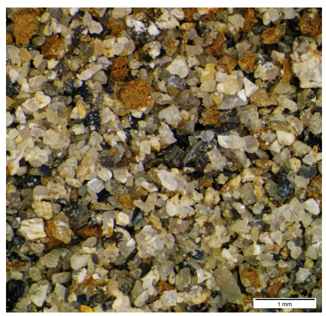
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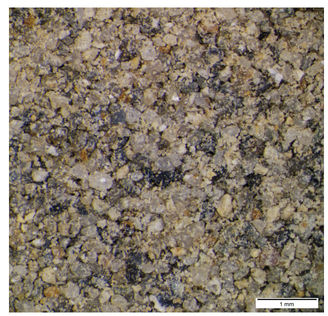
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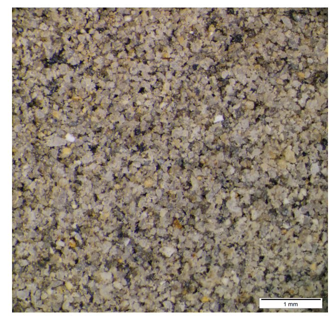
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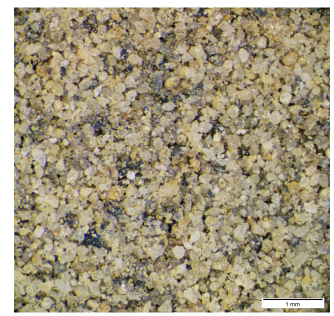
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**Plate I.** Photomicrographs (25x) of selected bedrock sandstones in North Dakota: 1. Fox Hills Formation in Morton Co., 2. Hell Creek Formation in Morton Co., 3. Ludlow Formation in Bowman Co., 4. Cannonball Formation in Morton Co., 5. Bullion Creek Formation in Billings Co., 6. Bullion Creek Formation in Billings Co., 7. Bullion Creek Formation in Billings Co., 8. Bullion Creek Formation in Billings Co., 9. Basal sandstone of the Sentinel Butte Formation in Billings Co., 10. Basal sandstone of the Sentinel Butte Formation in Billings Co., 11. Basal sandstone of the Sentinel Butte Formation in Billings Co., 12. Basal sandstone of the Sentinel Butte Formation in McKenzie Co., 13. Basal sandstone of the Sentinel Butte Formation in McKenzie Co., 14. Basal sandstone of the Sentinel Butte Formation in Billings Co., 15. Basal sandstone of the Sentinel Butte Formation in Billings Co., 16. Sentinel Butte Formation in McKenzie Co., 17. Sentinel Butte Formation sandstone in McKenzie Co., 18. Sentinel Butte Formation sandstone in McKenzie Co., 19. Sentinel Butte Formation sanstone in Billings Co.

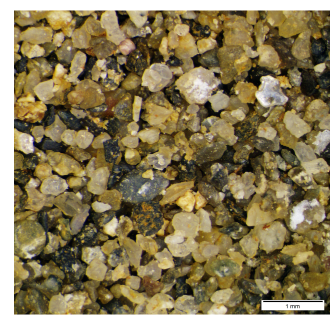
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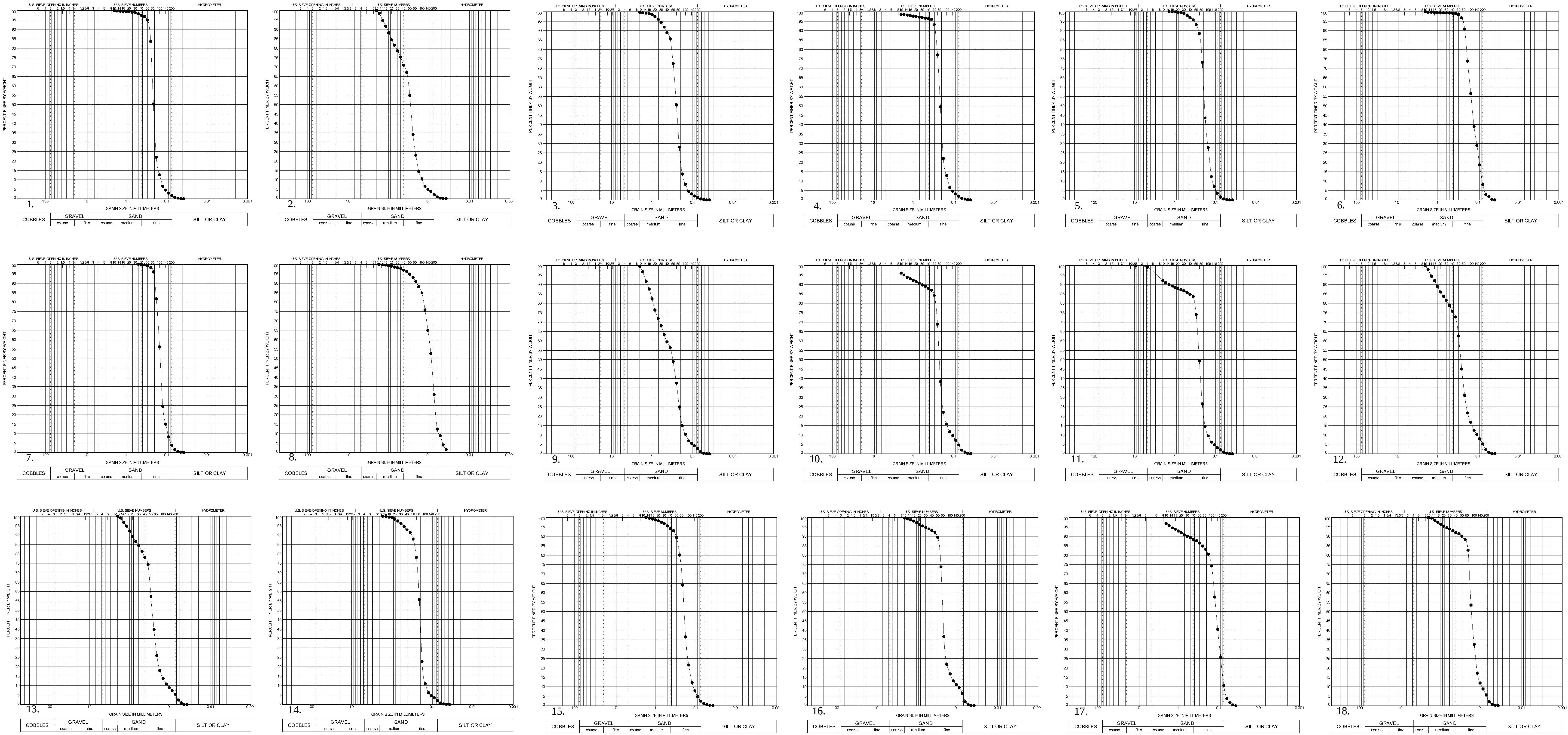
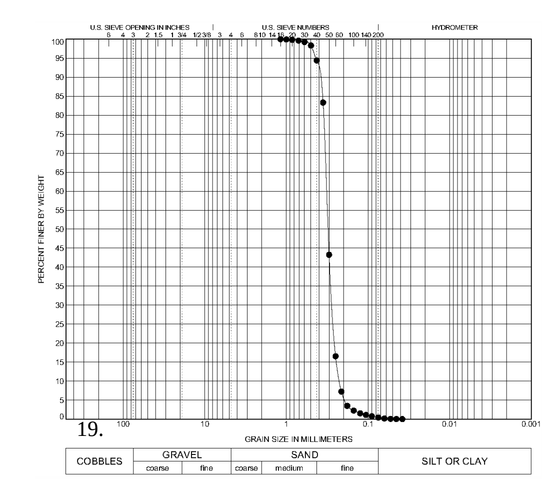
**Plate II.** Sieve analyses of selected bedrock sandstones in North Dakota.

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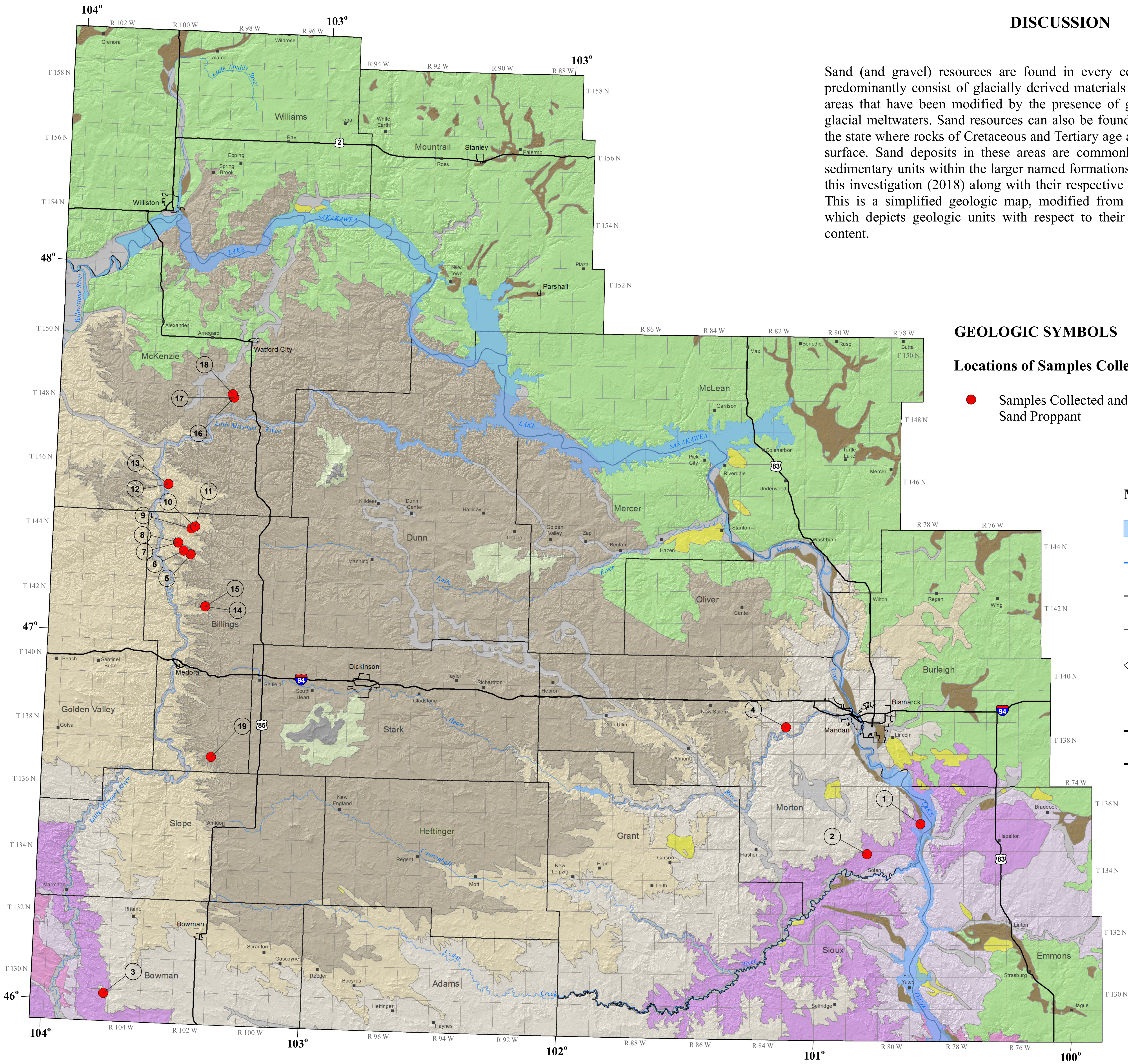
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

# Generalized Bedrock and Surface Geology and Selected Bedrock Sample Locations




## DISCUSSION

Sand (and gravel) resources are found in every county in North Dakota and predominantly consist of glacially derived materials that have been deposited in areas that have been modified by the presence of glacial ice and/or associated glacial meltwaters. Sand resources can also be found in the southwestern part of the state where rocks of Cretaceous and Tertiary age are found and exposed at the surface. Sand deposits in these areas are commonly found as smaller bedded sedimentary units within the larger named formations. The sample locations from this investigation (2018) along with their respective sample numbers are plotted. This is a simplified geologic map, modified from Clayton and others (1980), which depicts geologic units with respect to their sand (and gravel) resource content.

## GEOLOGIC SYMBOLS

### Locations of Samples Collected During Investigation

Samples Collected and Tested for Use as Natural Sand Proppant

### Misc Symbols

- Water
- Major Rivers or Creeks
- County Boundaries
- Township Boundaries
- City/Town Boundaries
- City/Town Locations
- Interstate Highway
- US Highway

Scale 1:1,000,000

0 10 20 30 40 Miles

0 10 20 30 40 Kilometers

North American Datum 1983 Lambert Conformal Conic

## EXPLANATION

### QUATERNARY

**Fluvial Sand**

Cross-bedded sand; as thick as 30 feet (10 meters); originally deposited on flood plains. Commonly found within channels of modern streams and rivers.

**Eolian Sand**

Windblown, well sorted, fine grained sand up to 30 feet (10 meters)thick, occurring as dune deposits.

**Glaciofluvial Sand & Gravel**

Well sorted to moderately well-sorted sand and gravel up to 100 feet (30 meters) in thickness. Commonly found as outwash plains or as terrace deposits along modern streams and rivers.

**Glacial Drift**

Unsorted, unbedded, mixture of sand, silt, clay, with pebbles and occasional boulders (till).

### TERTIARY

**WHITE RIVER GROUP**

**CHADRON and BRULE FORMATIONS (undifferentiated)**

Light colored sand and clay overlain by pinkish siltstone, clay, and sand.

### PALEOCENE-EOCENE

**GOLDEN VALLEY FORMATION**

Yellow-brown sandstone, sand, silt, and clay.

**SENTINEL BUTTE FORMATION**

Gray-brown silt, sand, clay, sandstone, and lignite.

**BULLION CREEK FORMATION**

Yellow-brown silt, clay, sandstone, and lignite.

**LUDLOW, CANNONBALL and SLOPE FORMATIONS (undifferentiated)**

Gray-olive-yellow-brown siltstone, shales, and sandstones with lignite.

### CRETACEOUS

**HELL CREEK FORMATION**

Gray sand, silt, clay, and sandstone.

**FOX HILLS FORMATION**

Olive-brown sand, shale, and sandstone.

**PIERRE FORMATION**

Dark-gray shale.

Cartographic Compilation: Navin Thapa