Eolian Sands in North Dakota Evaluated for use as Natural Sand Proppant for Oil & Gas Wells

By

Fred J. Anderson

GEOLOGIC INVESTIGATION NO. 207
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
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On the cover: Mosaic of aerial oblique image looking towards the northwest across high-relief dunes (Riverdale Ridge) in southwestern Sargent county west of Brampton, North Dakota and a ground-based photograph oriented to the east of a high dune of the northern high dunes area in this dune complex along with a representative photomicrograph (25x) of dune sand from this location.

Abstract

A re-evaluation into the potential use of eolian sands found in North Dakota as natural sand proppants for use in the hydraulic fracturing of oil and gas wells in the Williston Basin was conducted during the 2017-2019 biennium. Gradational analysis was performed on samples from 20 selected eolian sand areas which consisted of an average of 91% sand, 5% silt, and 4% clay. Two samples were tested and characterized from the largest of the 36 eolian sand deposits found in North Dakota, the Denbigh Dunes area, 22 miles northeast of Minot, North Dakota, for potential use as natural proppant sands for oil and gas well hydraulic fracturing using current testing standards and recommendations published by the International Organization for Standards (ISO), the American National Standards Institute (ANSI), and the American Petroleum Institute (API). These testing standards include: grain-size distribution determination (i.e. gradational analysis) via sieve analysis, determination of sand crush resistance, HCL-HF acid solubility, determination of individual grain sphericity and roundness, sand sample turbidity, and sand density determinations including bulk and apparent (i.e. specific gravity) densities. Overall, the percent of fines loss on sample prepatory wash from bulk samples No. 1 & 2 was 30% and 4.9 %. Testing and analysis results on prepared 40/70 (Sample No. 1) and 30/50 (Sample No. 2) sized samples indicated crush resistance values of <2K and 5K, HCL-HF acid solubilities ranged 16.6% and 6.4%, along with average sphericity and roundness values of 0.6 and 0.5, respectively. ISO mean particle diameters of 0.239 mm and 0.428 mm, turbidities of 85 and 18 FTU, bulk densities of 76.8 and 89.9 pcf and an average specific gravity of 2.62 g/cm^3. Reported % clusters were ~1/100 for Sample No. 1 and none in the field of count for Sample No. 2. XRD mineralogic analysis on Sample No. 1 reported total clays of 8% with smectites and illites being the dominant clay minerals. Total silicates were at 85% with quartz being the dominant silicate mineral at 57%. Total carbonates were 6% with dolomite present at 4%, and iron minerals reported at 1%.

Acknowledgements

The author would like to thank the private landowners who participated in this investigation and submitted sand samples from their respective properties of interest to be included for testing and characterization. Cartographic support was provided by Mr. Navin Thapa, GIS Specialist with the North Dakota Geological Survey. Original proppant testing services were provided by Stim-Lab, Inc., Duncan, Oklahoma. Additional materials testing was completed by the N.D. Department of Transportation's Materials and Research Division in Bismarck, North Dakota.

Author's Note

This re-evaluation was conducted in response to requests by the Oil and Gas Industry in North Dakota 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 in recognition of the current oil and gas industry trend towards the relaxation of proppant testing specifications in favor or more regional or local proppant sand source utilization. The intent of this investigation was to characterize selected eolian sand sources for potential use as proppants by using applicable testing methodologies recommended for the testing and evaluation of natural sands as proppants as published by ISO, ANSI, API and current practice in the oil and gas industry.

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LIST OF ABBREVIATIONS

ANSI – American National Standards Institute
API – American Petroleum Institute
FTU – Formazin Turbidity Units
GIS – Geographic Information Systems
HCL-HF – Hydrochloric-Hydrofluoric Acid
ISO – International Organization for Standards
NDGS – North Dakota Geological Survey
NDSSCC – North Dakota State Soil Conservation Committee
NIFC – No Clusters Observed in Field of Count
Psi – pounds per square inch
Pcf – pounds per cubic foot
XRD – X-Ray Diffraction

BACKGROUND

Introduction

The evolving success of the Bakken\Three Forks oil play in North Dakota, through hydraulic fracturing and 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 the upper-Midwestern U.S. and Texas. Most recently, developing trends in oil and gas well production economics 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 this rapidly changing production dynamic the North Dakota Geological Survey (NDGS) is continuing the investigation of North Dakota's eolian (i.e. wind-blown) sand resources for potential use as natural sand proppant. During a previous proppant sand investigation (Anderson, 2011), the public and the sand and gravel industry in North Dakota were engaged and encouraged to submit samples from their respective deposits of interest to be evaluated and potentially tested for characterization as a natural sand proppant. This report includes results of proppant characterization testing on selected eolian sands (i.e. Denbigh Dunes east of Minot) that were submitted by private landowners and recently completed sedimentological analyses for the majority of remaining areas containing eolian sand deposits.

EOLIAN SANDS IN NORTH DAKOTA

Location and Distribution

Eolian (windblown) sands occur across 3.6 % of the state covering an area totaling 2,560 square miles (~1.6 million acres). These deposits are distributed dominantly in the eastern two-thirds of the glaciated portions of the state (Figure 1).

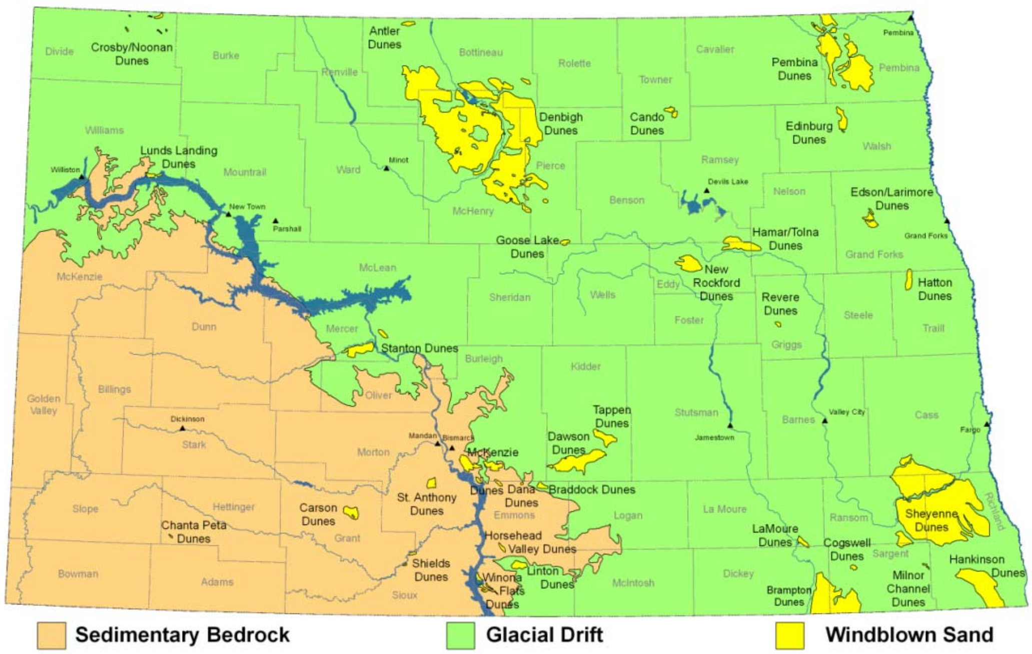


Figure 1. Areas in North Dakota where eolian (windblown) sands occur in dune deposits.

Dunes are found in nearly every region of the state, but tend to generally diminish in distribution and areal extent as one moves west with the exception of the Denbigh Dunes area west of Minot. This is due, in part to North Dakota's recent glacial past which aided in the reworking and depositing of younger, immature sediments. These sediments were scoured and reworked from the underlying bedrock, as the consequence of the actions and interaction of advancing and retreating glacial ice and flowing and accumulating glacial meltwaters.

There are five areas in the state where the expanse of eolian sand deposits is greater than 100 square miles. These include: the Denbigh Dunes in north-central North Dakota, the Sheyenne, Hankinson, and Brampton (Riverdale Ridge) Dunes in southeastern North Dakota, and the Pembina Dunes in northeastern North Dakota (Table 1).

Table 1. Locations of selected dune areas found in North Dakota

Dune Area	Counties Occurring	Area (mi^2)
Denbigh Dunes	McHenry\Pierce\Bottineau	990
Sheyenne Dunes	Ransom\Sargent\Richland	687
Pembina Dunes	Cavalier\Pembina	208
Brampton (Riverdale Ridge) Dunes	Dickey\Sargent	152
Hankinson Dunes	Richland	110
Dawson Dunes	Kidder	73

Eolian sands found in North Dakota are well-sorted, fine to very-fine grained (Figure 2), with mineral compositions reflective of the localized glaciofluvial and glaciolacustrine deposits from which they typically originated.

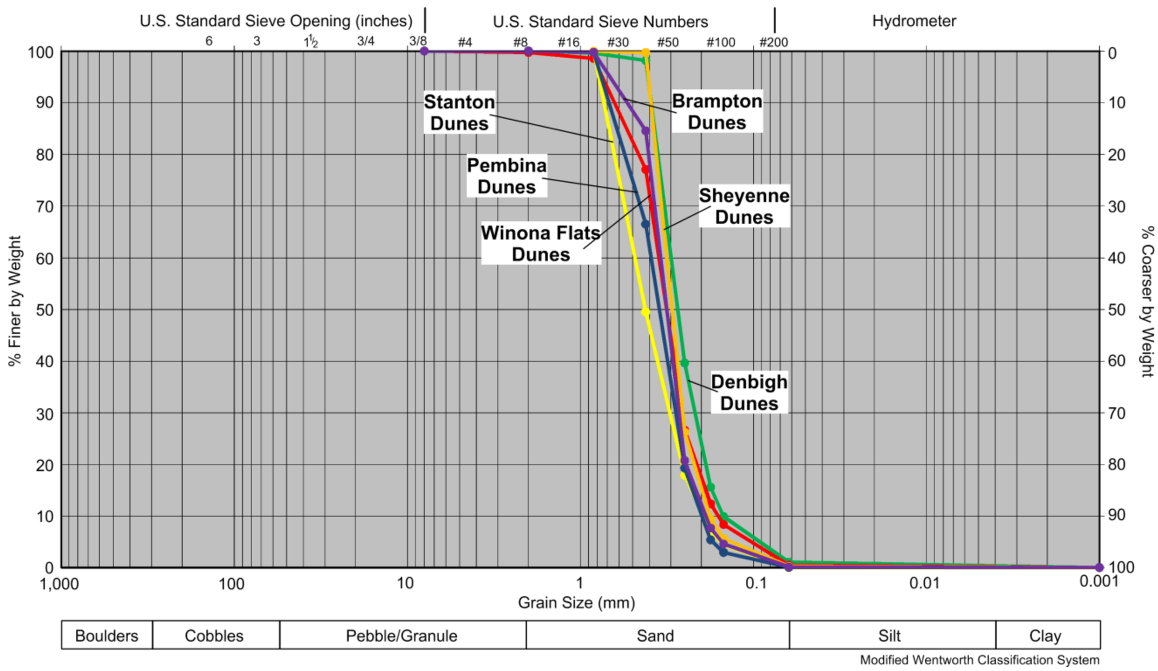


Figure 2. Grain-size distributions of selected dune sands in North Dakota. Grain sizes of the Brampton (Riverdale Ridge) area dunes (purple curve), Denbigh (green curve), Pembina (blue curve), Sheyenne (orange curve), Stanton (yellow curve), and Winona Flats Dunes (red curve) all plot within the medium to very fine sand size range.

Denbigh Dunes

The most notable sand dunes in North Dakota are likely the expanse of dunes near Denbigh, North Dakota. Some researchers, who have conducted smaller scale studies on eolian features found across North America, have also called the Denbigh dunes area the Minot Dune Field. The Denbigh Dunes cover an area of 990 square miles (~633.300 acres) or about 28 standard townships in north-central North Dakota in McHenry County. Local relief is as high as 65 feet with dunes typically 5-20 feet in height (Figure 3). The Denbigh area consists of northwest trending parabolic type (crescentric shaped) dunes that are classified as being inactive as they are currently stabilized by a well-developed cover of vegetation. These eolian sands are the windblown remnants of sand and gravel deposits left behind from Glacial Lake Souris. Sample No. 1 was collected from a large stabilized dune approximately three and a half miles northwest of Denbigh (Figure 4). Eolian sand found in the Denbigh Dunes area can be described as a quartz common, yellow-brown, well-sorted, fine to medium grained sand with dominantly angular to subrounded grains that is generally devoid of carbonates (Lemke, 1960, Lord, 1988, Anderson, 2010).

Figure 3. Aerial oblique view to the north of a high-relief portion of the Denbigh Dunes two miles northwest of Denbigh along N.D. Highway 2, McHenry County.

Figure 4. View to the north of grass covered high-relief dunes located just to the northwest of Denbigh, North Dakota, approximately 28 miles east of Minot.

Sheyenne Dunes

The Sheyenne Dunes, located in southeastern North Dakota cover an area of approximately 687 square miles (~440,000 acres) in northwestern Richland, eastern Ransom, and southern Cass counties. These dunes are the windblown accumulate of the sands deposited on the Sheyenne Delta (Figure 5) during the time when the Sheyenne River emptied into the southern end of Glacial Lake Agassiz about 12,000 thousand years ago (Arndt, 1977).

Figure 5. View to the north across a high-relief dune area of the Sheyenne Dunes along County Road 18 in northeastern Richland county, approximately four miles south of the Sheyenne River.

Pembina Dunes

The Pembina Dunes are located in northeastern North Dakota and cover an area of approximately 208 square miles (~133,243 acres) in western Pembina County. These eolian sand deposits (Figure 6) are the windblown accumulate of the sands deposited on the Pembina Delta, during the time when the Pembina River emptied into the northern end of Glacial Lake Agassiz, about 12,000 thousand years ago (Arndt, 1977).

Figure 6. View to the north of a dune face along Pembina County Road 5 in the southern Pembina Dunes area in east-central Pembina County. This location is approximately three miles northeast of Concrete.

Brampton Dunes (Riverdale Ridge)

There are several additional areas in the state where eolian sand deposits are located, such as the Riverdale Ridge portion of the Brampton Dunes area in southwestern Sargent County (Figures 7 & 8), the Winona Flats Dunes in southeastern Emmons County (Figures 9 & 10) and the Hazen-Stanton Dunes in southeastern Mercer County (Figure 11). These areas are much smaller than the dune areas left behind near the margins of glacial lakes (i.e. Glacial Lakes Souris and Agassiz). Dune fields with areal extents significantly less than 100 square miles include the McKenzie Dunes in southwestern Burleigh County, the New Rockford Dunes in central Eddy County, the Stanton Dunes in southeastern Mercer and southwestern McLean County, the Tappen Dunes in southeastern Kidder County, the Edinburg Dunes in north-central Walsh County, the Carson Dunes in northeastern Grant County, the Edson\Larimore Dunes in west-central Grand Forks County, the Hatton Dunes in northwestern Traill County, the Winona Flats and Linton Dunes in southwestern Emmons County, the Hamar\Tolna Dunes in southeastern Ramsey, northeastern Eddy, and western Nelson Counties and several additional areas (Figure 1) where dune deposits occur with areal extents less than ten square miles.

Figure 7. Aerial oblique view to the northwest across the high-relief area of the Brampton Dunes (Riverdale Ridge) area in western Sargent County.

Figure 8. View to the east of the large sand dune in north portion of the Brampton Dunes (Riverdale Ridge) area in southeastern North Dakota. This dune is one of the larger and more visually impressive sand dunes found in North Dakota.

Dune Fields in North Dakota

A dune field is comprised of an area where several dunes have accumulated as a result of winds transporting the relatively finer fractions of sediment from a source area (commonly along a former river or stream) into localized accumulations in the form of dunes. A dune field commonly contains several individual or complex dune types and may be interspersed with interdune areas where local vegetation has become abundant, and may be bounded by large accumulations of tabular-like deposits known as sheet sands. For the purposes of discussion here, a dune field or dune area is understood to contain of all of the localized sand sized deposits (both sheet sands and dune sands) that have been moved or modified by the wind.

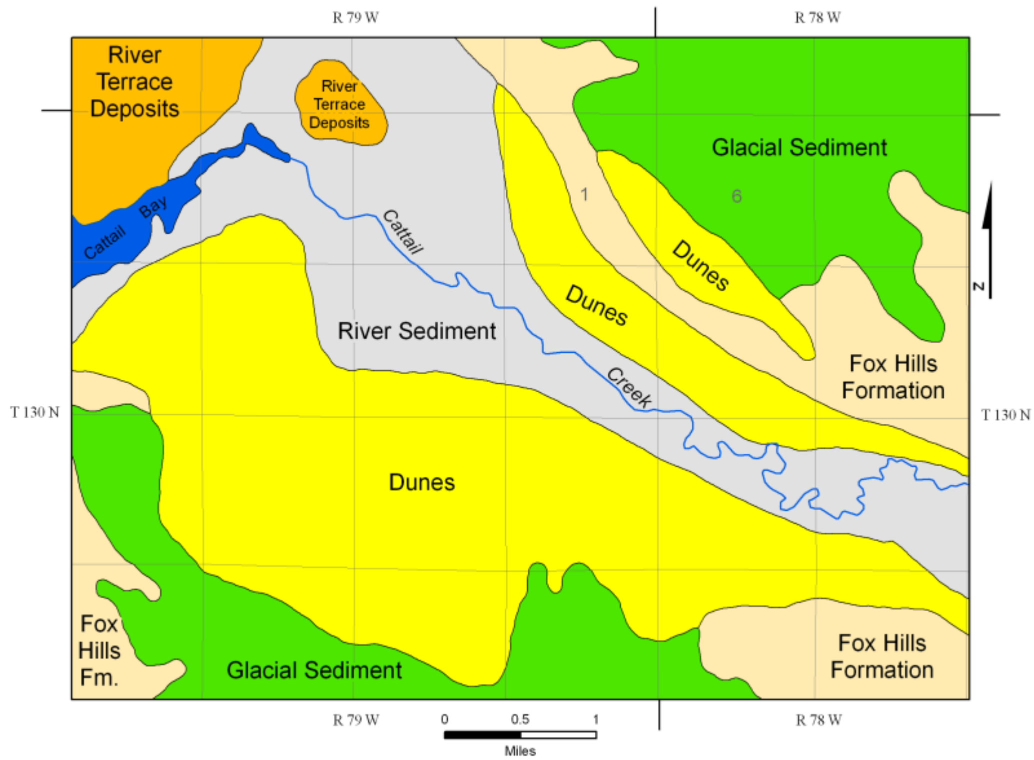


Figure 9. Map of bedrock and surface geologic units in the southeastern Cattail Bay-Winona Flats area in southwestern Emmons County along the Missouri River. Dunes are present on both the north and south sides of Cattail Creek and resulted when the finer portions of these water-deposited sediments, were reworked by the wind into dunes.

Most of the sand dunes found in North Dakota are the crescentric (parabolic) or longitudinal (linear) types (Figure 10). Areas that contain linear dunes tend to be more expansive with relatively lesser amounts of localized relief. Conversely, areas found to contain parabolic or crescentric dunes tend to be more clustered together with higher local relief and often contain numerous blowouts (Figure 11).

Figure 10. View to the northwest into the Missouri River Valley at Cattail Bay (south of Winona Flats) from N.D. Highway 1804 across the dune field south of Cattail Creek in southwestern Emmons County. The low-relief undulating topography of these grass covered dunes is characteristic of many of the wind-swept areas where dunes are present in North Dakota.

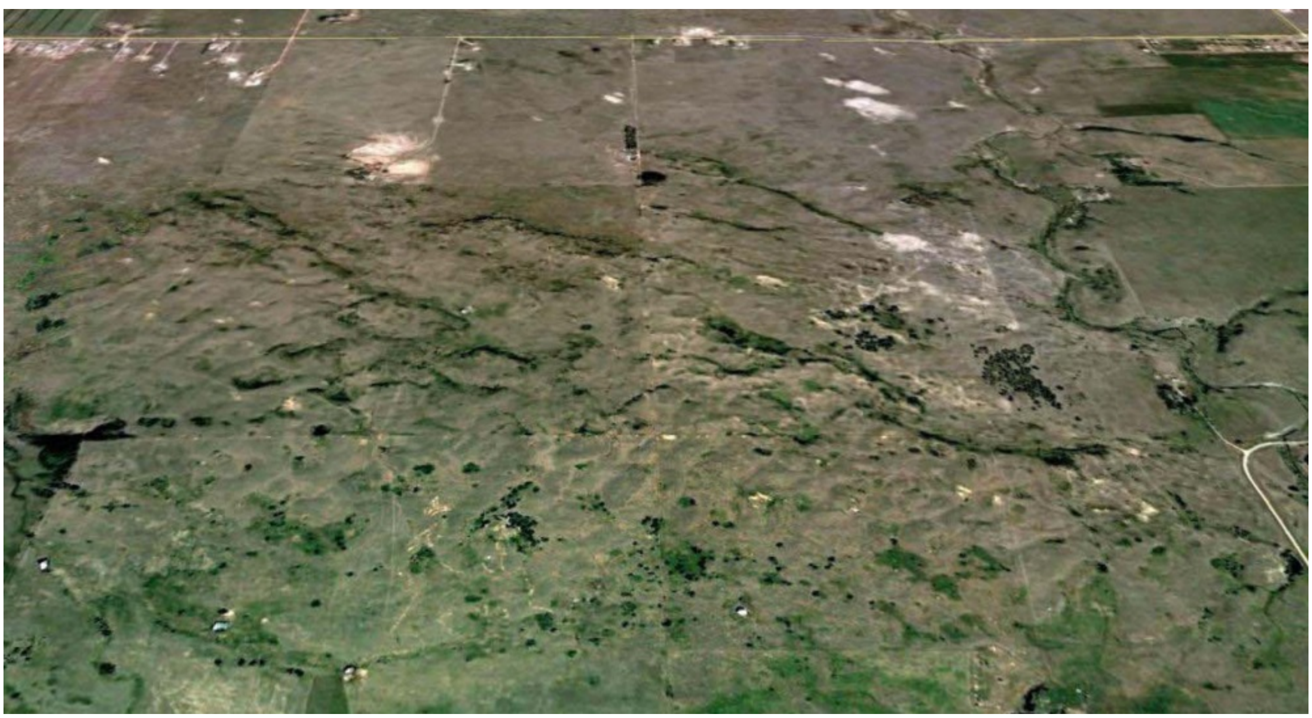


Figure 11. Expansive sand dune field located between Hazen and Stanton south of the Knife River drainage in southeastern Mercer county in central North Dakota. This aerial oblique image is of the southwestern portion of the dune field near Hazen.

Dune Structure

There are many types of dunes and each is formed from the ever-changing interactions of the wind and sand that is being carried along. An idealized sand dune (Figure 12) has the crest at its highest point and two sides, generally one longer than the other, which are referred to as the stoss (windswept side) and the lee (slipface side) side. When multiple dunes are present, such as in a dune field, the distance between each successive dune crest is called the dune wavelength. and, In conjunction with dune height and the size and mineralogy of sand particles within the dune, dune wavelength can be used to interpret the geologic environment and source of the sands (the provenance) during the time of dune formation. As sand particles are transported by the wind along the dune from the stoss to the lee side, they are blown up and over the crest after which they cascade along the slipface and, over time, build up into individual bedforms on the leading edge of the dune as it continues its downwind migration. The lee or downwind side of a dune is commonly steeper than the windward side, but will not typically exceed an angle of 34^{O}. This angle is the commonly accepted value for the angle of repose for loose dry sand.

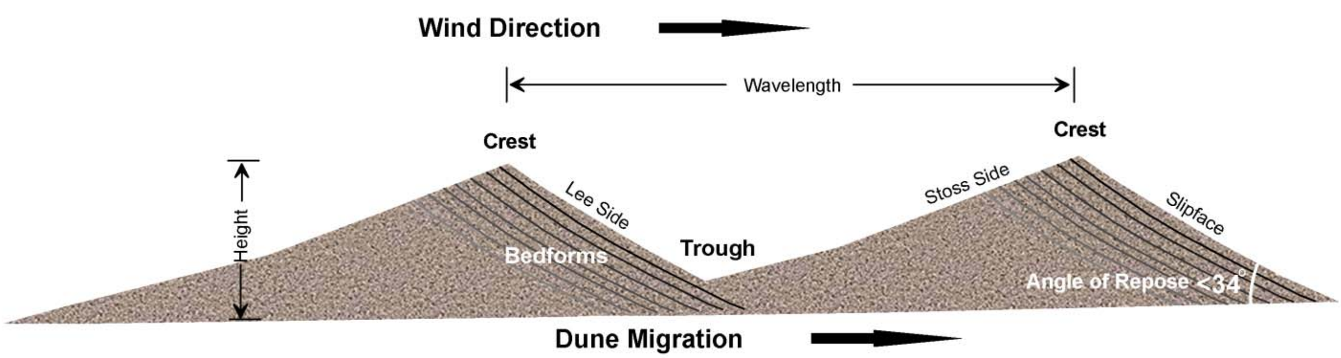


Figure 12. Schematic cross-section of a pair of idealized dunes illustrating some basic descriptive characteristics of the dune landform.

By looking at the orientation of the dune crests and individual dune characteristics, clues to the eolian conditions responsible for dune creation can be used to interpret the geologic environment at the time of dune formation. As an example, previous workers have deduced that the northwest trending dunes of the Denbigh Dunes [Minot Dune Field] were most likely the result of activities within the last 1,200 years or so. These dunes likely formed under climatic conditions more similar to that of today then to older post-glacial paleoclimatic conditions (Muhs, et al, 1997).

Dune Activity

When climatic conditions were recently much drier, for example during the 1930s drought period throughout the upper Midwest, several dune areas in the state were reactivated. In addition, dunes were created from freshly exposed sediment sources and many were found encroaching into rural settings (Figure 13b).

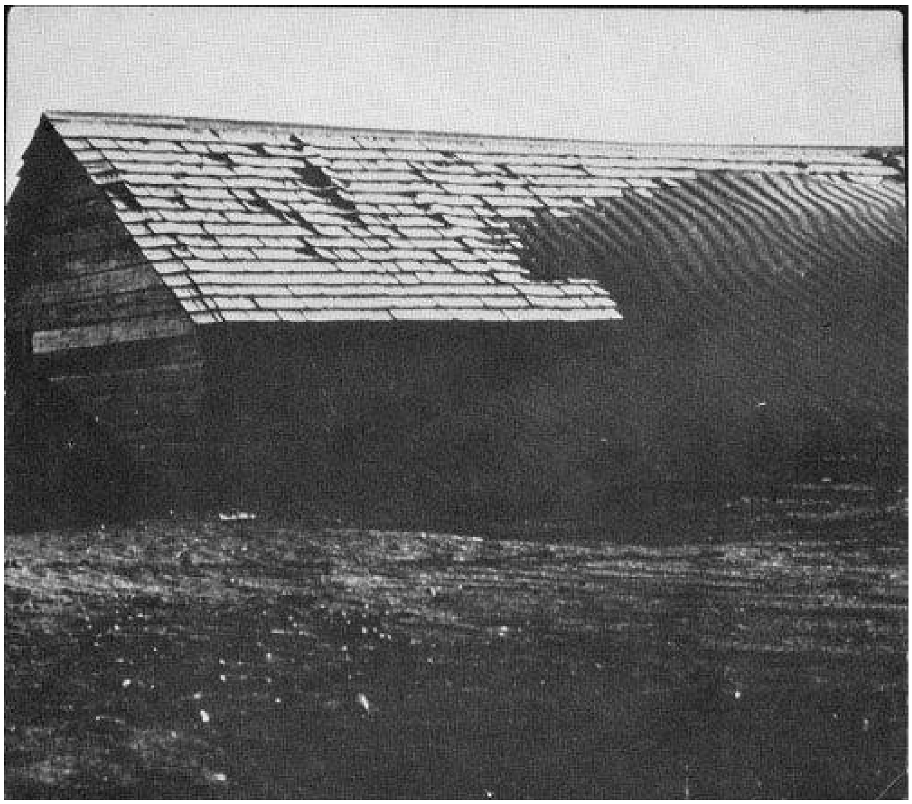


Figure 13. Sand dunes encroaching onto the side of a barn in Kidder County during the 1930's drought. Sand ripples can be seen on the surface of the dune indicating that the direction of sediment transport was parallel to the face of the roof (SHSND, ca. 1930).

It is generally well recognized that the eolian sands in North Dakota are Pleistocene to Holocene in age and have seen two to three different periods of activation throughout their existence, generally occurring during times of considerably drier paleoclimatic conditions.

PHOTOMICROGRAPH SUMMARY OF SELECTED DUNE AREAS

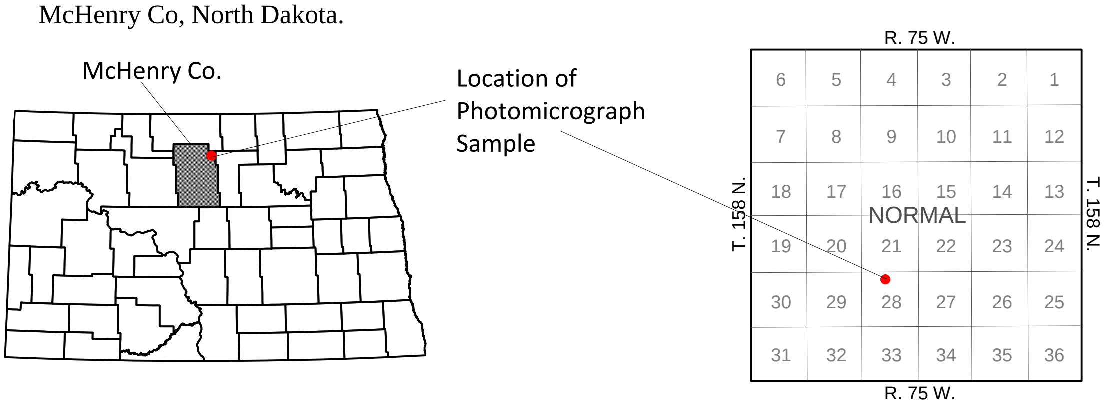
Representative bulk sand samples were collected from dune areas visited during the 2009 through 2011 field seasons. Representative cuts from each sample were digitally photographed at 25x magnification using a Wild Heerbrugg M8 binocular microscope with an attached Olympus D72 camera using the Olympus 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 (Figures 14 – 33) for detailed evaluation of sand grain morphology and mineralogical composition.

Denbigh Dunes *(northeast)*

NE1/4, NW1/4, 158-75-28

The Denbigh Dunes make up the largest area of eolian sand deposits in North Dakota. They cover an area of approximately 990 square miles, dominantly in McHenry county in north-central North Dakota. These fine- to medium-grained, well-sorted (poorly graded) sands are the windblown remnants of sand and gravel deposits left behind from the former Glacial Lake Souris and are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and detrital lignites. Topographic relief on these stabalized dunes can be as high as 65-feet. This sample was obtained from an area of dunes with relatively high topographic relief in northeastern McHenry county.

Figure 14. Photomicrograph (25x) of eolian sand from the northeast Denbigh Dunes in northeastern McHenry Co, North Dakota.



Denbigh Dunes *(northwest)*

SW1/4, SW1/4, 160-80-34

The Denbigh Dunes make up the largest area of eolian sand deposits in North Dakota. They cover an area of approximately 990 square miles, dominantly in McHenry county in north-central North Dakota. These fine- to medium-grained, well-sorted (poorly graded) sands are the windblown remnants of sand and gravel deposits left behind from the former Glacial Lake Souris and are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and detrital lignites. Topographic relief on these stabalized dunes can be as high as 65-feet. This sample was obtained from an area of dunes with low topographic relief in southwestern Bottineau county.

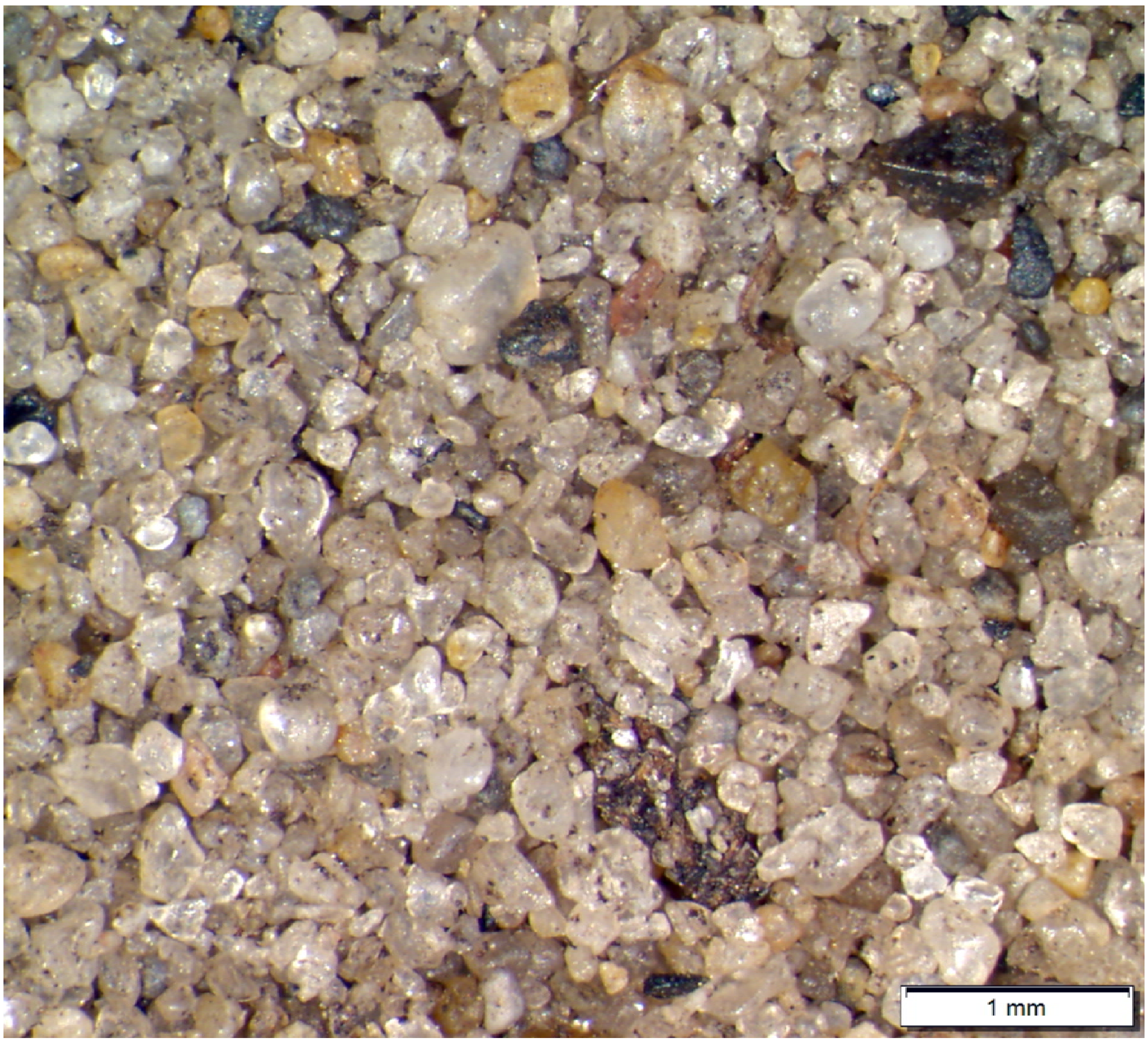
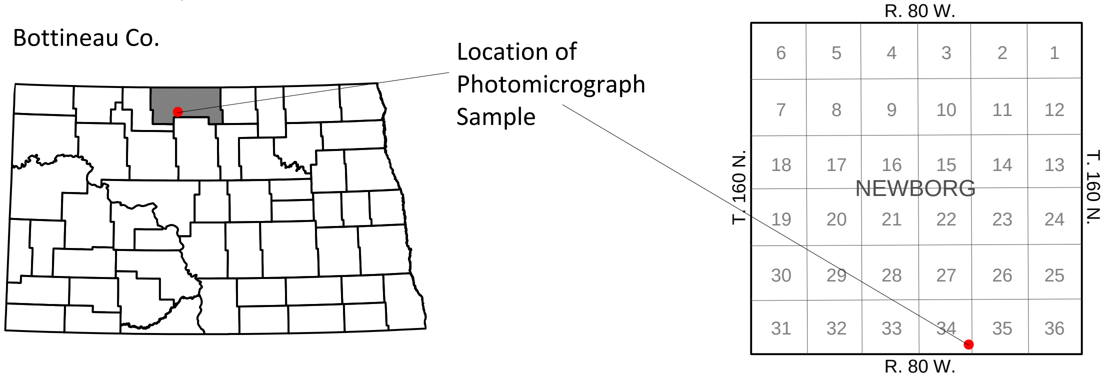


Figure 15. Photomicrograph (25x) of eolian sand from the northwest Denbigh Dunes in southwestern Bottineau Co, North Dakota.



Denbigh Dunes *(central)*

SW1/4, SW1/4, 156-77-6

The Denbigh Dunes make up the largest area of eolian sand deposits in North Dakota. They cover an area of approximately 990 square miles, dominantly in McHenry county in north-central North Dakota. These fine- to medium-grained, well-sorted (poorly graded) sands are the windblown remnants of sand and gravel deposits left behind from the former Glacial Lake Souris and are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and detrital lignites. Topographic relief on these stabalized dunes can be as high as 65-feet.

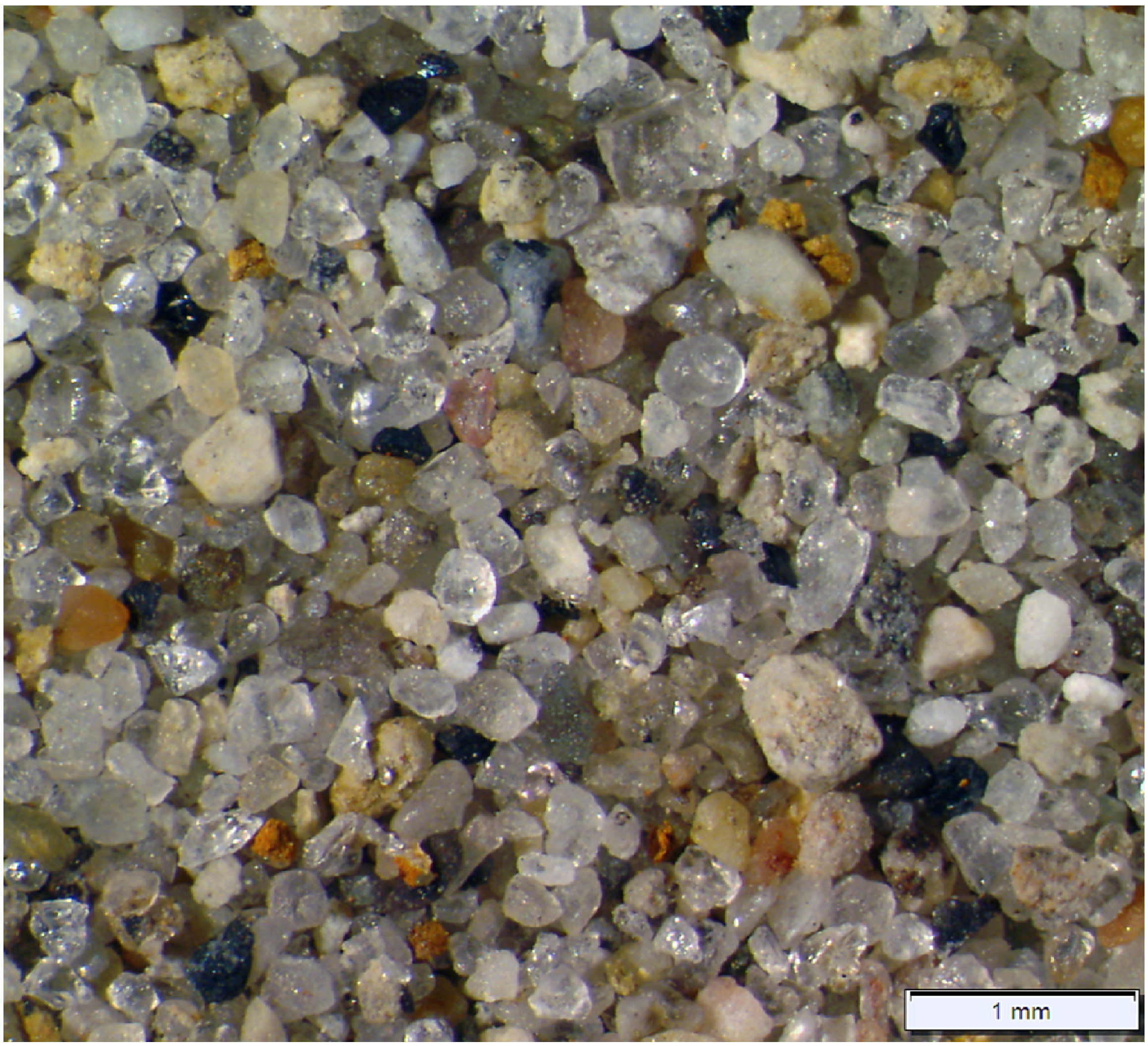
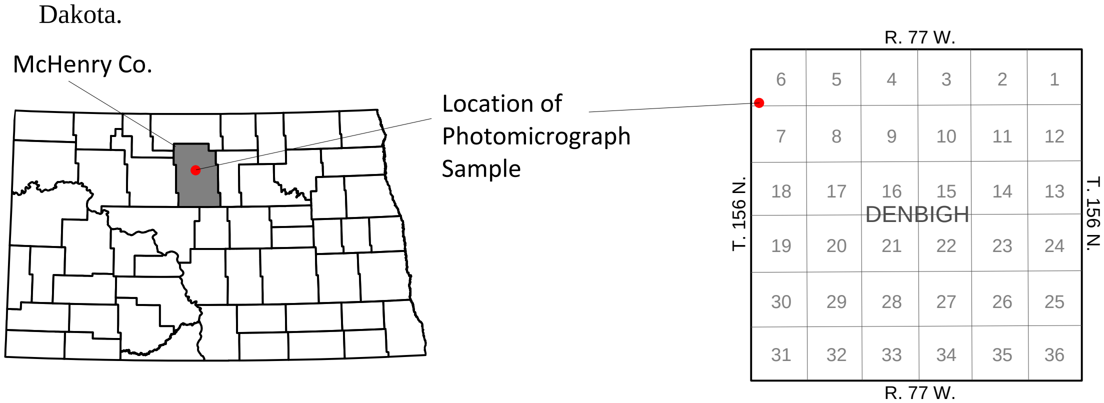


Figure 16. Photomicrograph (25x) of eolian sand from the Denbigh Dunes in Central McHenry Co, North Dakota.

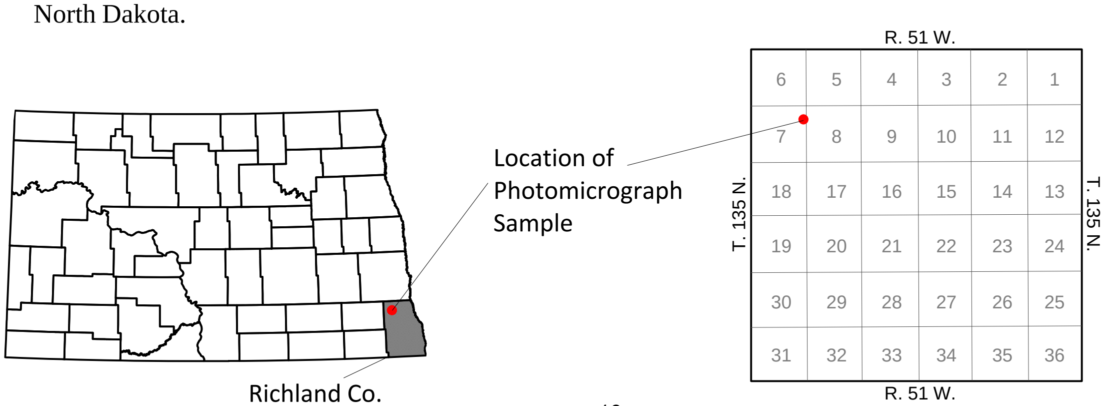


Sheyenne Dunes

NE1/4, NE1/4, 135-51-7

The Sheyenne Dunes make up the second largest area of eolian sand deposits in North Dakota. They cover an area of approximately 687 square miles, dominantly in northwestern Richland county in southeastern North Dakota. These fine-to medium-grained, well-sorted (poorly graded) sands are the windblown accumulate of sand and gravel deposits of the Sheyenne Delta created when the Sheyenne River emptied into the southern end of Glacial Lake Agassiz around 12,000 years ago. The dunes are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and detrital lignites. Topographic relief on the high-dune areas can be as high as 30-feet.

Figure 17. Photomicrograph (25x) of eolian sand from the Sheyenne Dunes in northwestern Richland Co, North Dakota.

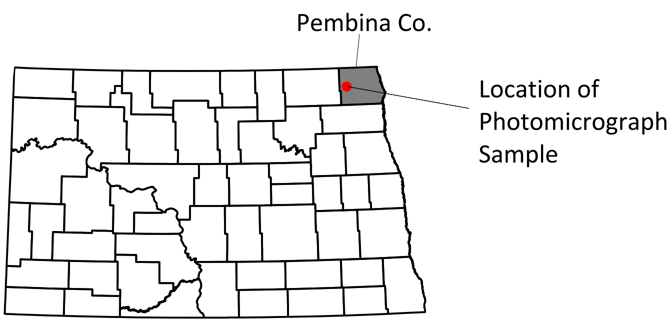


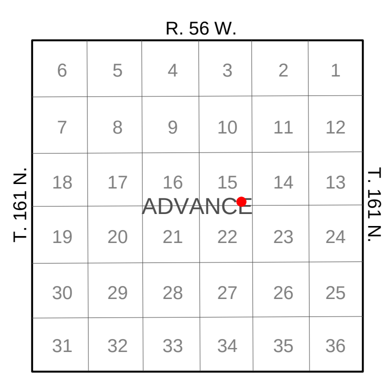
Pembina Dunes

SE1/4, SE1/4, 161-56-15

The Pembina Dunes make up the third largest area of eolian sand deposits in North Dakota. They cover an area of approximately 208 square miles, dominantly in west-central Pembina county in northeastern North Dakota. These fine-to medium-grained, well-sorted (poorly graded) sands are the windblown accumulate of sand and gravel deposits of the Pembina Delta created when the Pembina River emptied into the northern end of Glacial Lake Agassiz around 12,000 years ago. The dunes are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignites. Topographic relief on the high-dune areas can be as high as 30-feet.

Figure 18. Photomicrograph (25x) of eolian sand from the Pembina Dunes in west-central Pembina Co, North Dakota.



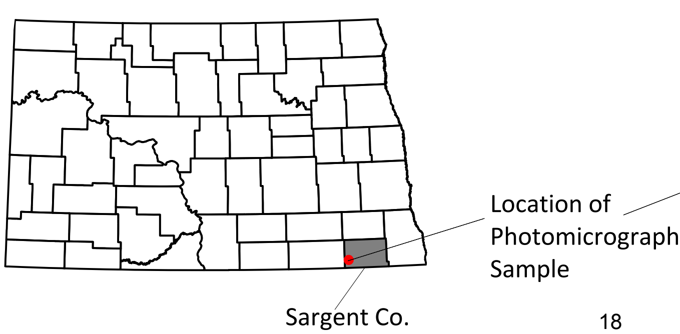


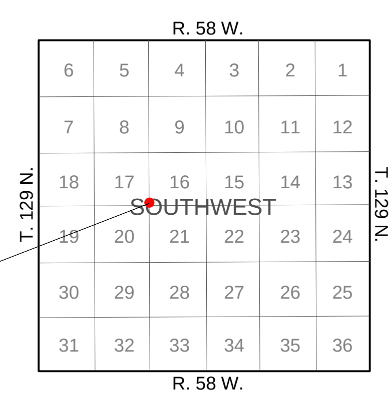
Brampton Dunes

SW1/4, SW1/4, 129-58-16

The northwest trending high-relief dunes (aka Riverdale Ridge) near Brampton, North Dakota have some of the most visually impressive eolian sand deposits in North Dakota. They cover an area of approximately 152 square miles, dominantly in southwest Sargent county and southeastern Dickey county in southeastern North Dakota. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignites. Topographic relief on the high-dune areas can be as high as 30-feet. It has been estimated that the in-place volume of sand in the high-relief dunes is nearly 1.5 MCY.

Figure 19. Photomicrograph (25x) of eolian sand from the Brampton Dunes (Riverdale Ridge) in southwes -tern Sargent Co, North Dakota.



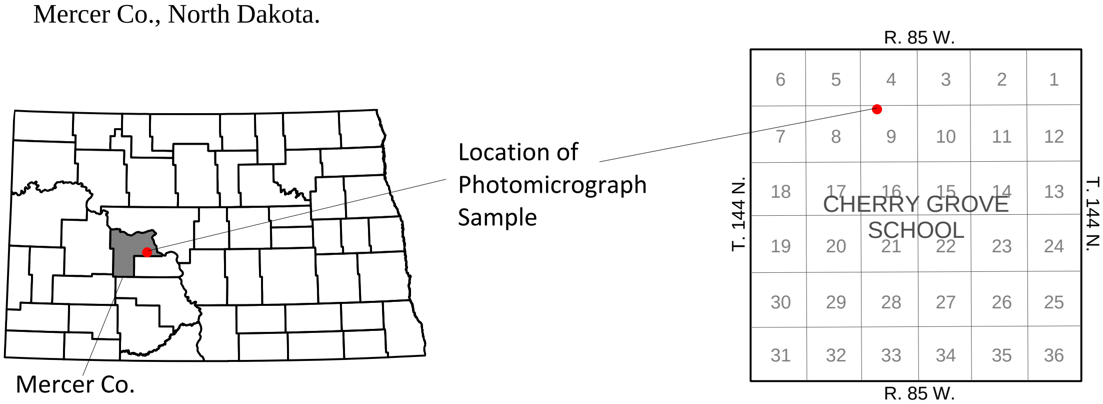


Hazen-Stanton Dunes (north)

NW1/4, NW1/4, 144-85-09

The Hazen-Stanton Dunes are low-relief dunes located on the south side of the Knife River between Hazen on the west and Stanton to the east in southeastern Mercer county. They cover an area of approximately 34 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

Figure 20. Photomicrograph (25x) of eolian sand from the Hazen-Stanton Dunes (north) in southeastern Mercer Co., North Dakota.



Hazen-Stanton Dunes (south)

NW1/4, SW1/4, 144-86-13

The Hazen-Stanton Dunes are low-medium relief dunes located on the south side of the Knife River bounded by Hazen on the west and Stanton to the east in southeastern Mercer county. They cover an area of approxim-ately 34 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

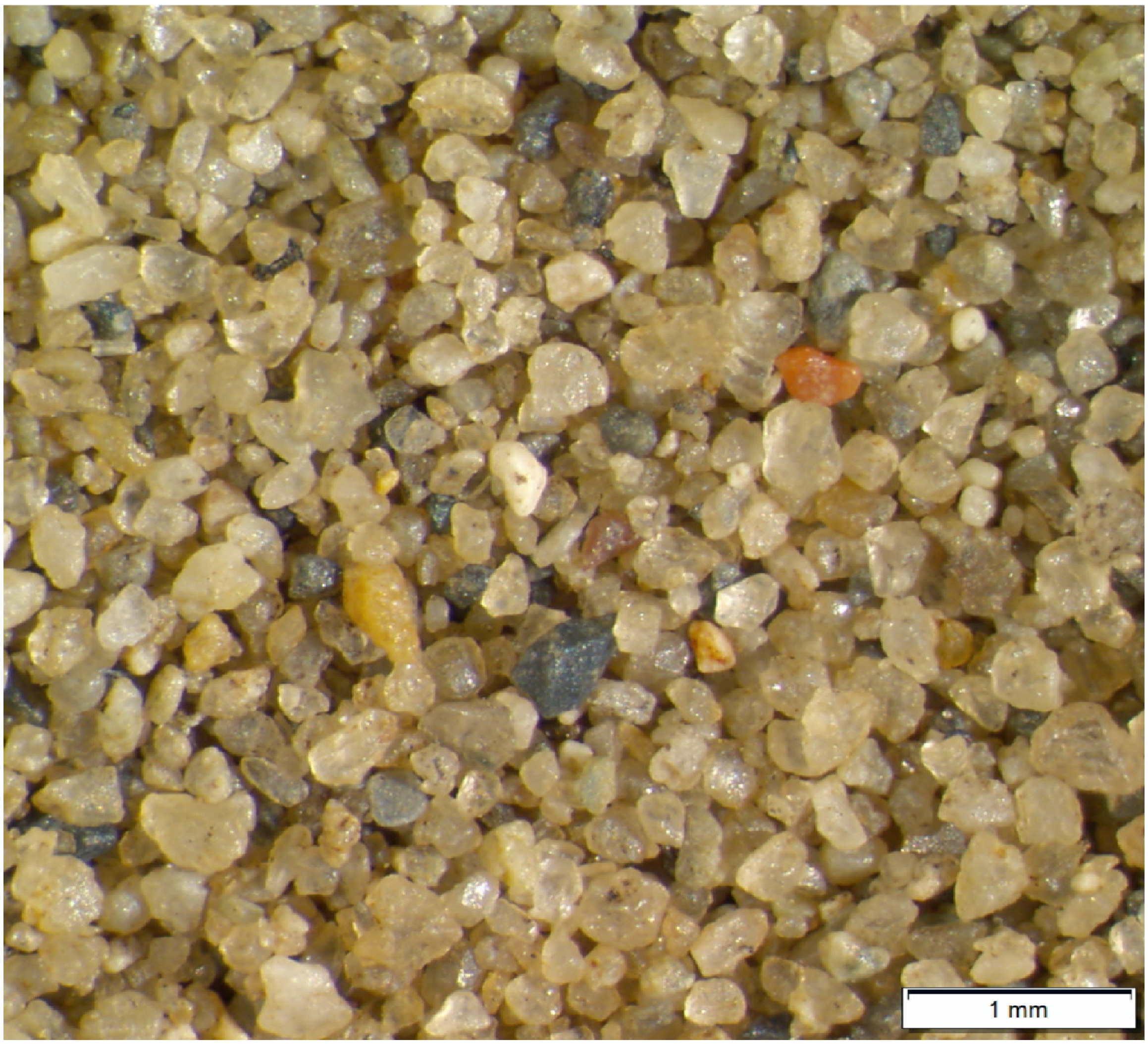
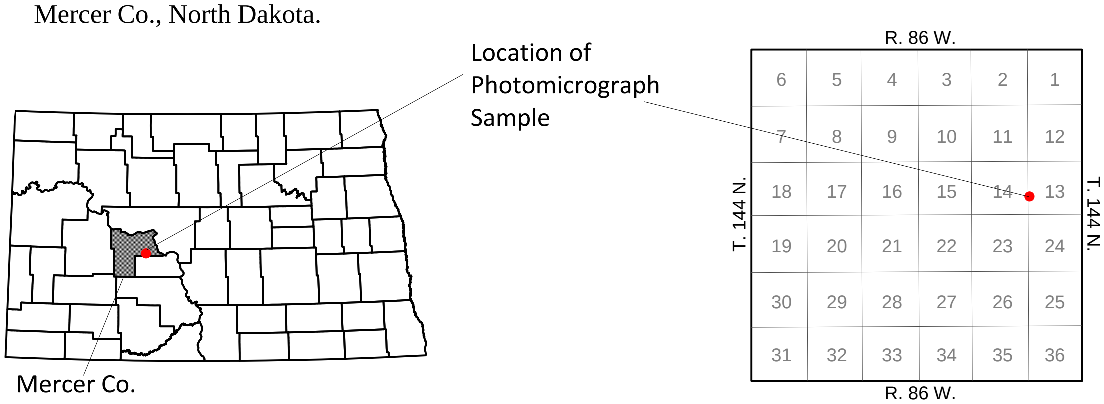


Figure 21. Photomicrograph (25x) of eolian sand from the Hazen-Stanton Dunes (south) in southeastern Mercer Co., North Dakota.

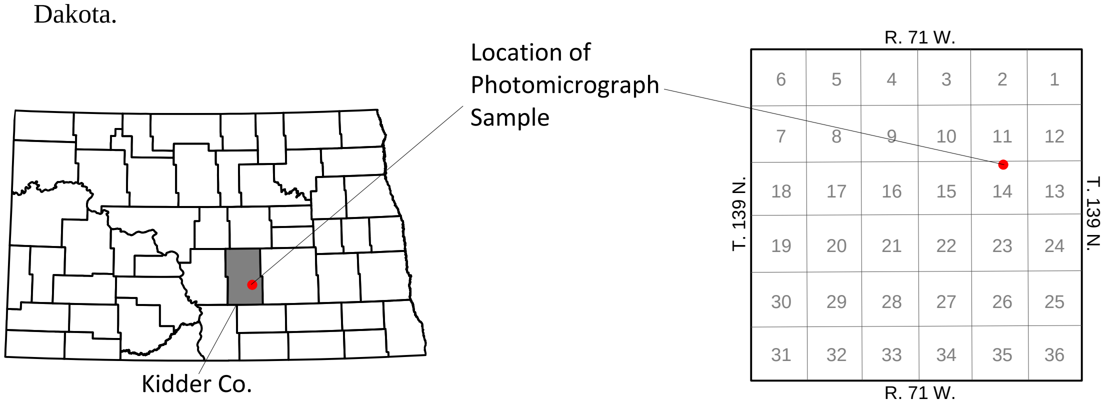


Tappen Dunes

NW1/4, NE1/4, 139-71-14

The Tappen Dunes are low-relief dunes located directly south of Tappen in southeastern Kidder county, North Dakota. They cover an area of approximately 21 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

Figure 22. Photomicrograph (25x) of eolian sand from the Tappen Dunes in southeastern Kidder Co., North Dakota.

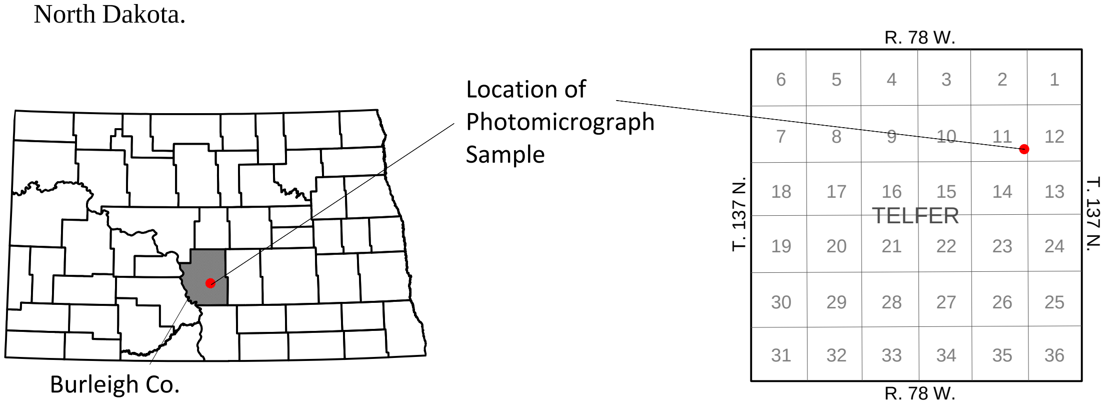


McKenzie Dunes

SW1/4, SW1/4, 137-78-11

The McKenzie Dunes are medium-relief dunes located approximately 14 miles southeast of Bismarck south of McKenzie, North Dakota in southeastern Burleigh county. They cover an area of approximately 40 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age and are the windblown accumulate of glaciolacustrine sediments deposited in the former Glacial Lake McKenzie which occupied the majority of southeastern Burleigh Co. during Wisconsinan time. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

Figure 23. Photomicrograph (25x) of eolian sand from the McKenzie Dunes in southwestern Burleigh Co, North Dakota.



Burleigh Co. Southeast (Lincoln Flats) Dunes SW1/4, NW1/4, 137-79-8

The Lincoln Flats Dunes are low-relief dunes located approximately 3 miles southeast of Bismarck and directly south of Lincoln, North Dakota in southeastern Burleigh county. They are a part of the McKenzie dunes which together cover an area of approximately 40 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age and are the windblown accumulate of glaciolacustrine sediments deposited in the former Glacial Lake McKenzie which occupied the majority of southeastern Burleigh Co. during Wisconsinan time. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

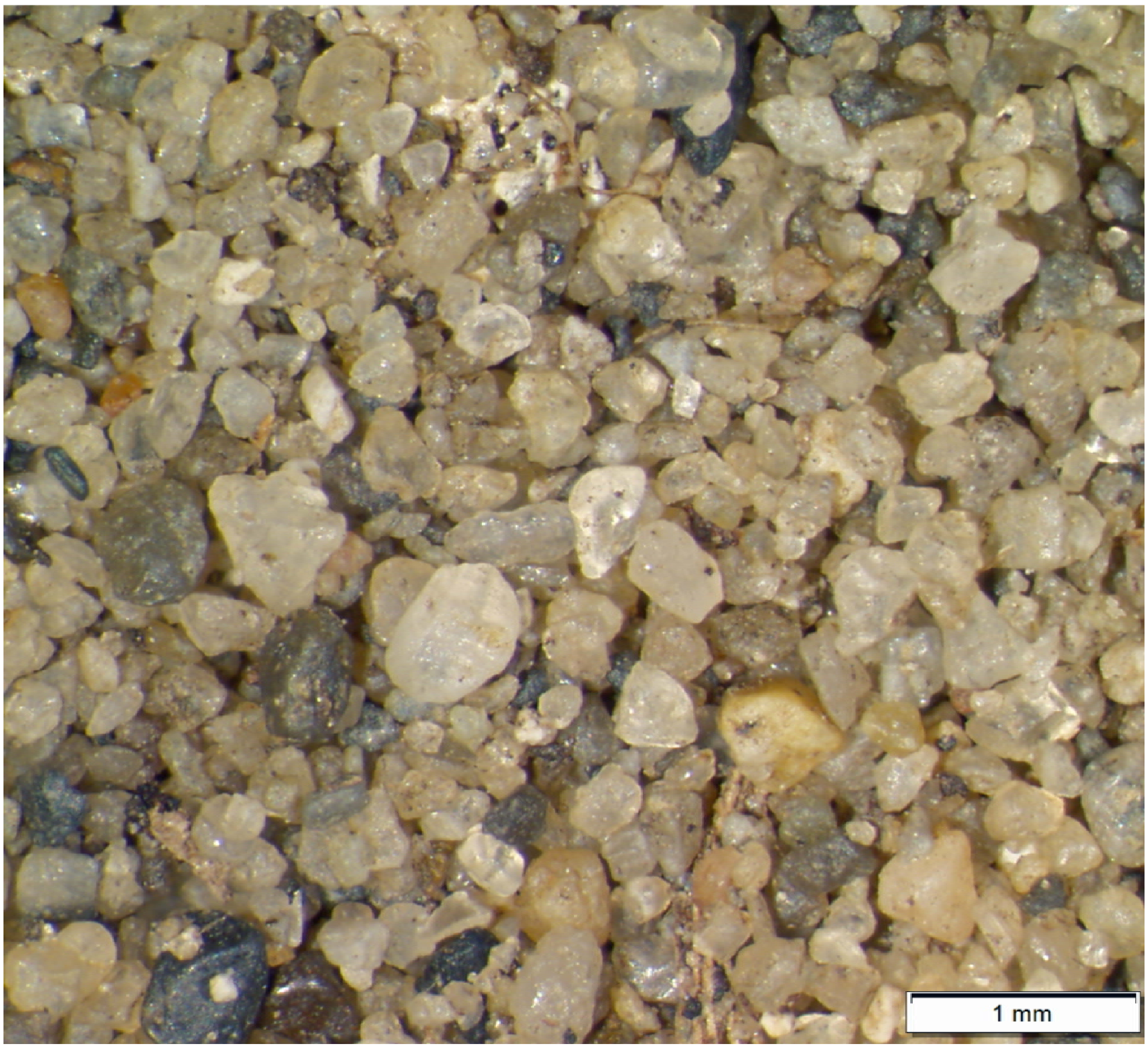
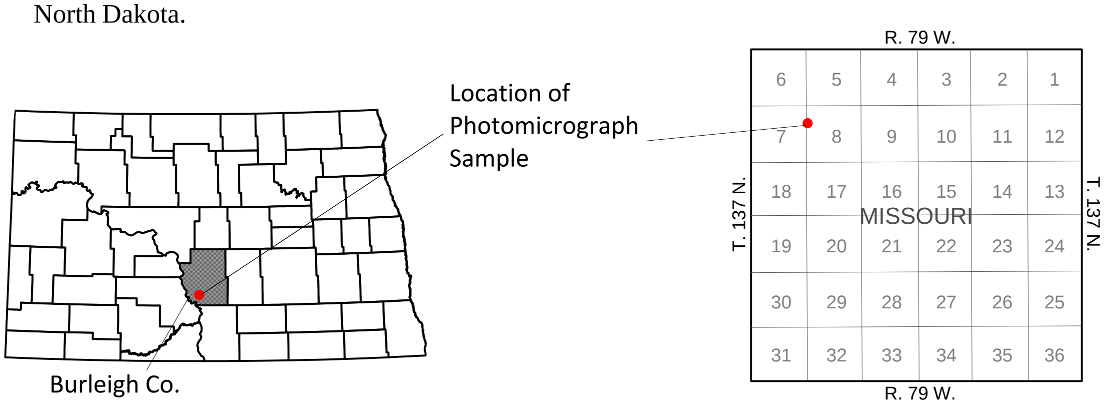


Figure 24. Photomicrograph (25x) of eolian sand from the Lincoln Flats Dunes in southeastern Burleigh Co, North Dakota.



Braddock Dunes

SW1/4, NW1/4, 136-75-09

The Braddock Dunes are low-relief dunes located approximately three miles north of Braddock in north-eastern Emmons county.northeast of Carson in northeastern Grant county, North Dakota. They cover an area of approximately six square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle -Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

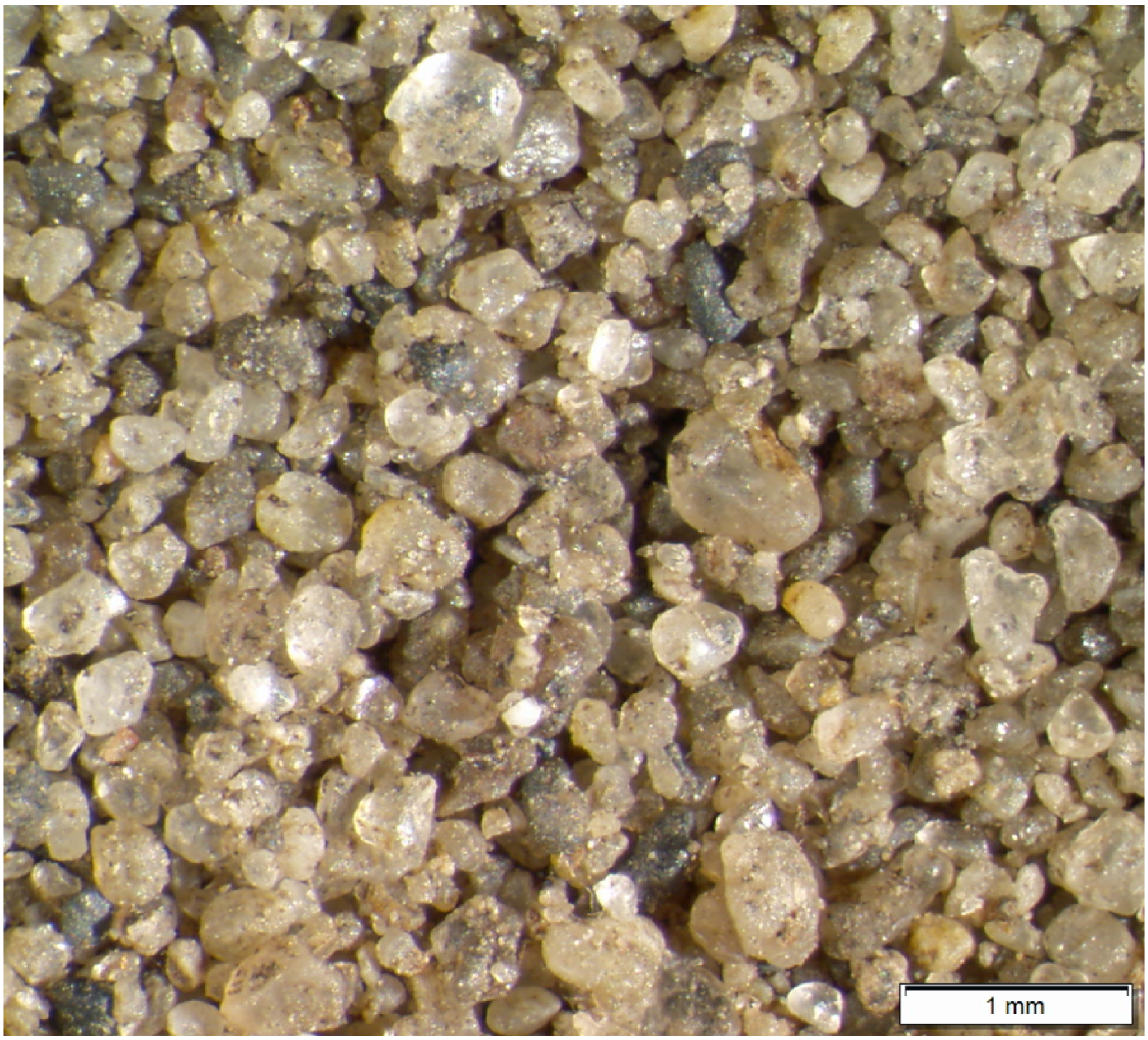
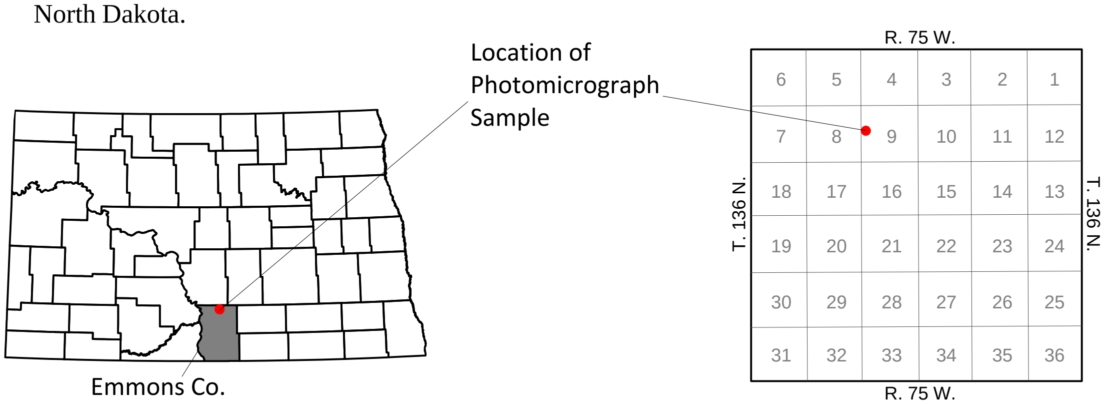


Figure 25. Photomicrograph (25x) of eolian sand from the Braddock Dunes in northeastern Emmons Co., North Dakota.



Long Lake Creek (Dana) Dunes

SE1/4, SW1/4, 136-76-05

The Long Lake Creek (Dana) Dunes are low-relief dunes located in north-central Emmons county. They cover an area of approximately three-quarters of a square mile. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age and are the windblown accumulate of glaciolacustrine sediments deposited along the Long Lake Creek drainage. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

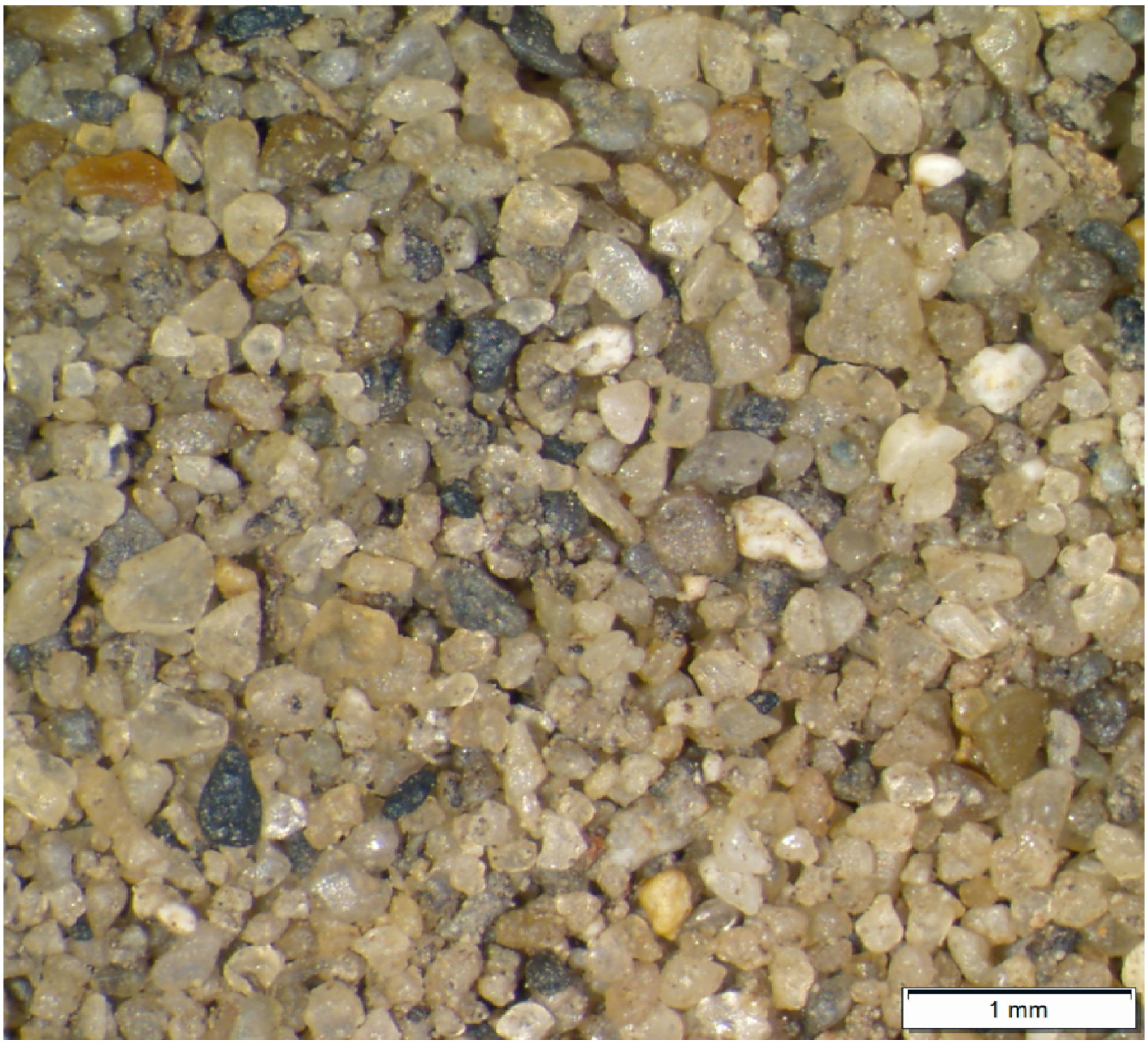
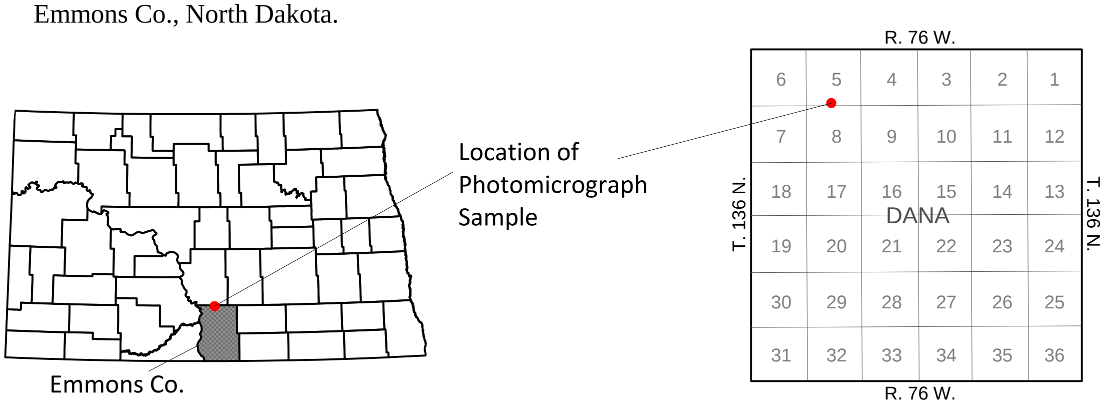


Figure 26. Photomicrograph (25x) of eolian sand from the Long Lake Creek (Dana) Dunes in north-central Emmons Co., North Dakota.



Horsehead Valley East Dunes

SW1/4, SE1/4, 133-78-24

The Horsehead Valley East Dunes are low-relief dunes located in west-central Emmons county. They cover an area of approximately three square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age and are the windblown accumulate of Tertiary bedrock of the surrounding Fox Hills Formation bordering the valley. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

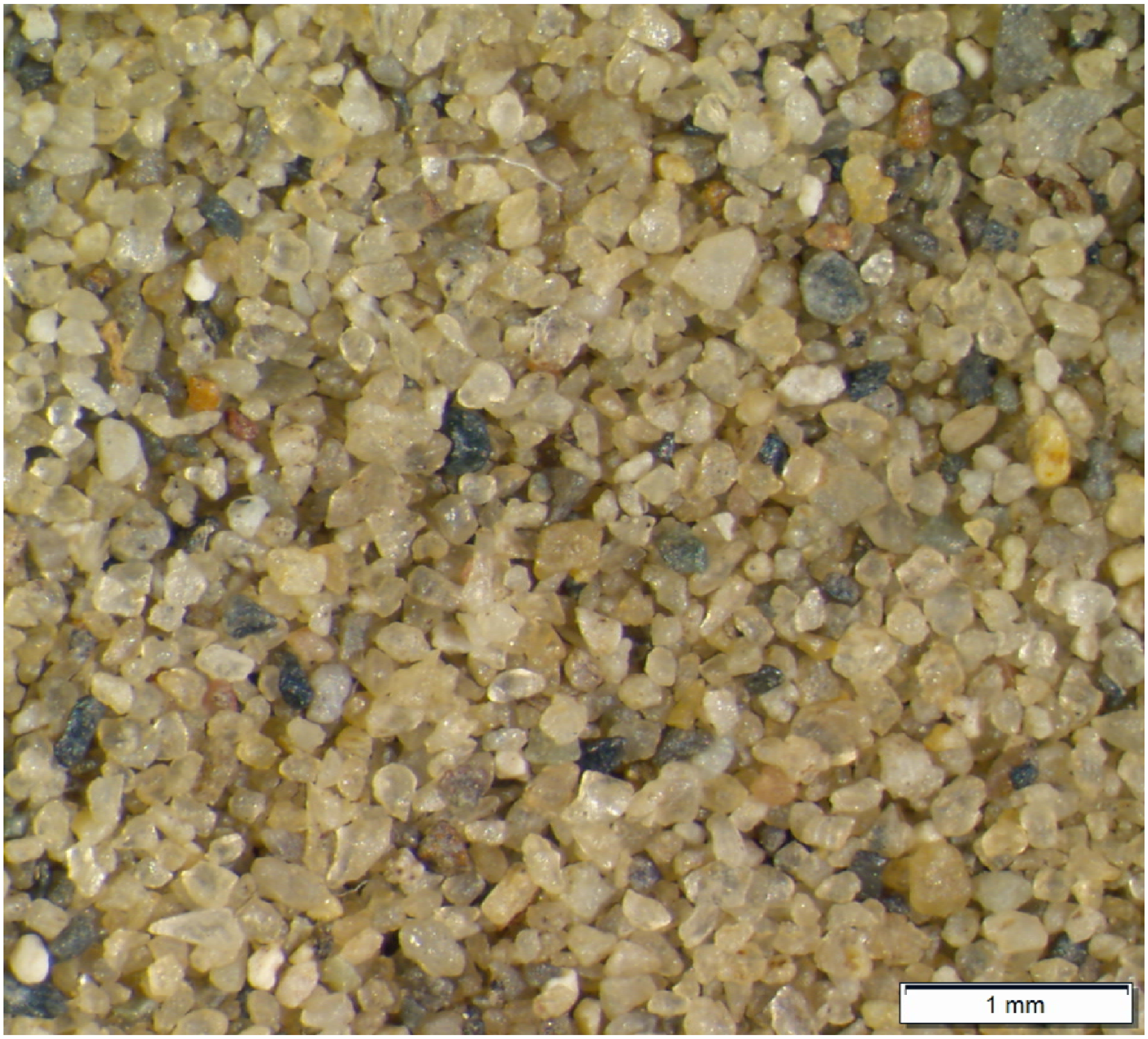
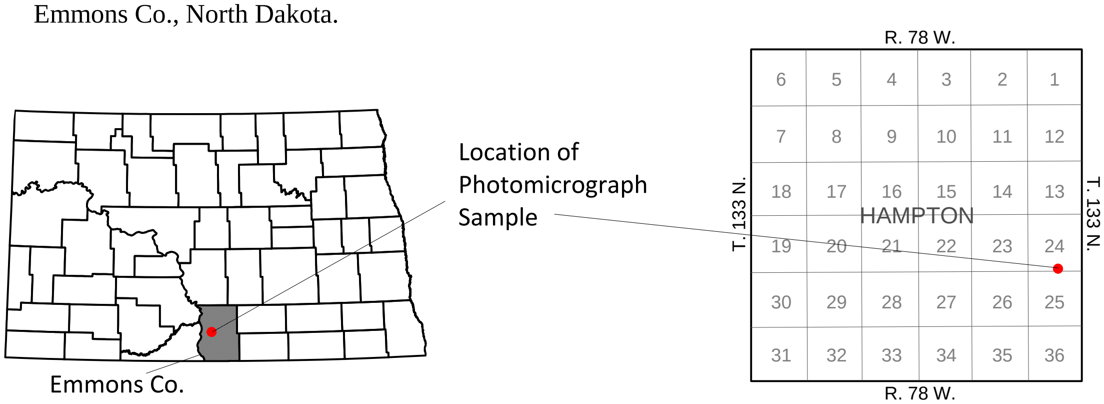


Figure 27. Photomicrograph (25x) of eolian sand from the Horsehead Valley East Dunes in west-central Emmons Co., North Dakota.

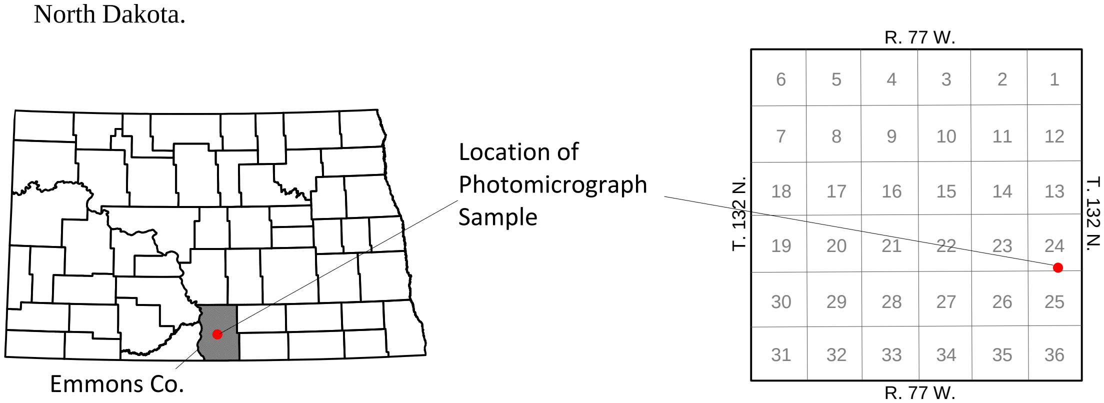


Linton Southwest Dunes

NW1/4, NE1/4, 132-77-24

The Linton Southwest Dunes are low-relief dunes located approximately four miles southwest of Linton in central Emmons county. They cover an area of approximately 12 square miles. These fine-to medium -grained, well-sorted (poorly graded) sands are middle-Holocene in age and are the windblown accumulate of glaciofluvial sediments deposited within the Beaver Creek drainage. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

Figure 28. Photomicrograph (25x) of eolian sand from the Linton Southwest Dunes in central Emmons Co., North Dakota.



Winona Flats Dunes

NE1/4, SE1/4, 130-79-14

The Winona Flats Dunes are low-relief longitudinal dunes arranged in a dune field that straddles Cat Tail Creek where it empties into the Missouri River in southwestern Emmons county. They cover an area of approximately 13 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age and are the windblown accumulate of glaciolacustrine sediments deposited along the Cat Tail Creek drainage. These sands have been modified into Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

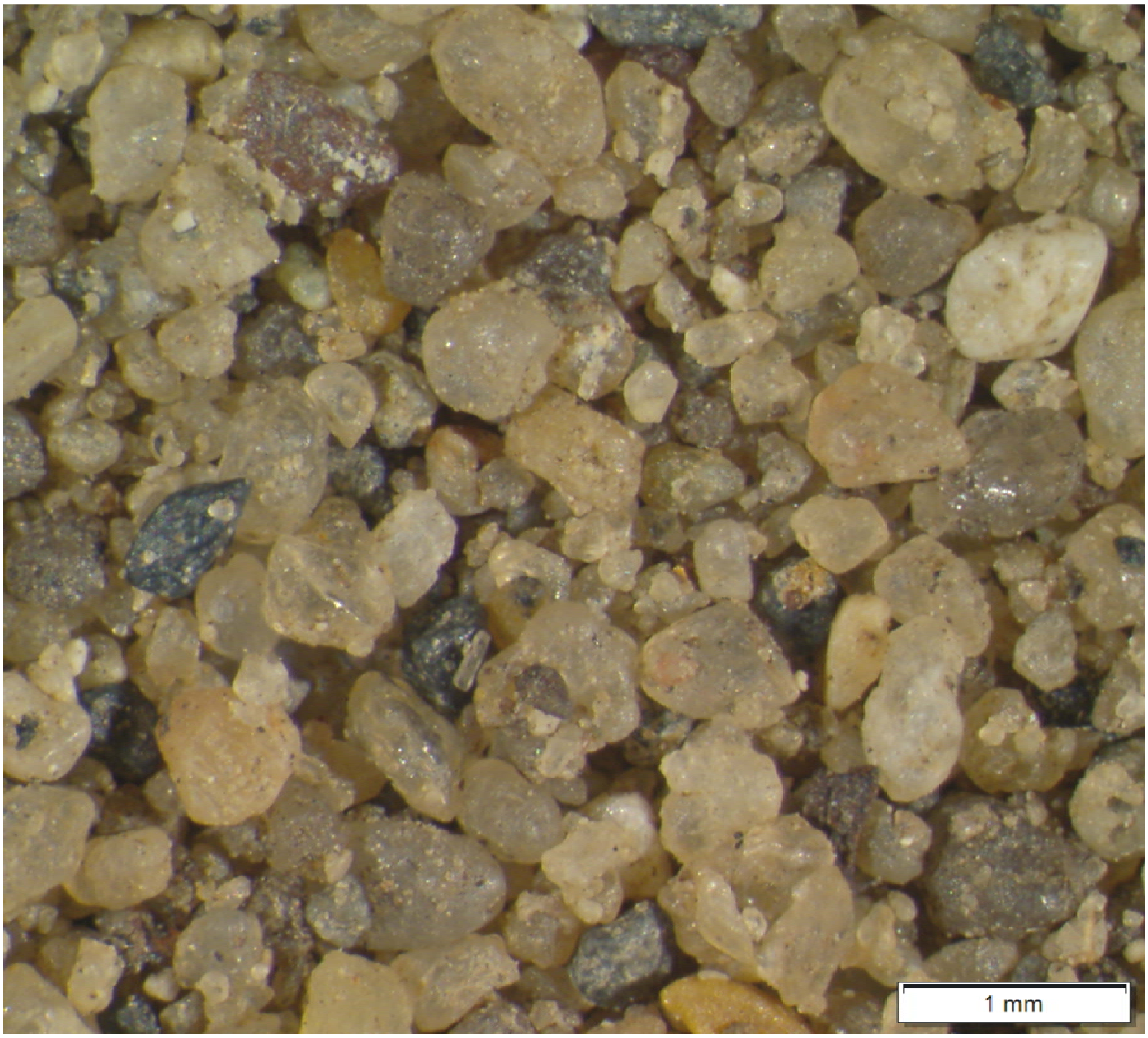
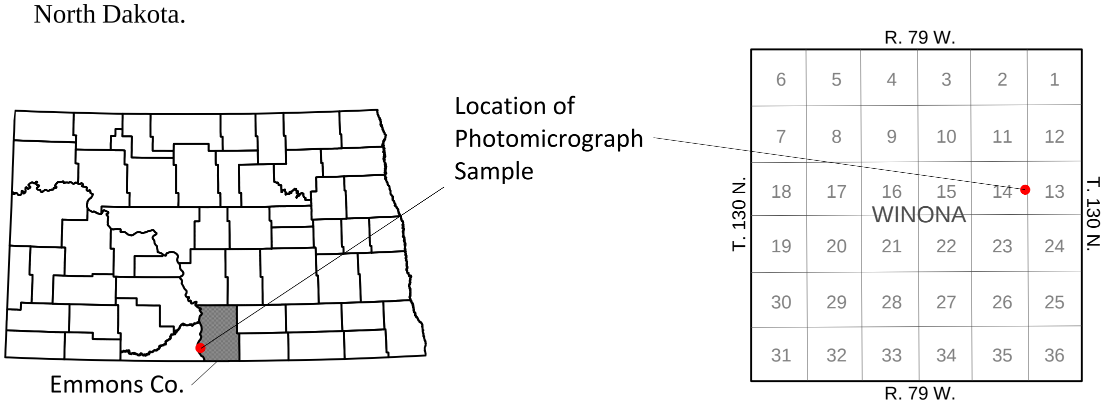


Figure 29. Photomicrograph (25x) of eolian sand from the Winona Flats Dunes in southwestern Emmons Co., North Dakota.



Carson Dunes

NE1/4, NW1/4, 135-86-31

The Carson Dunes are low-relief dunes located northeast of Carson in northeastern Grant county, North Dakota. They cover an area of approximately 16 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

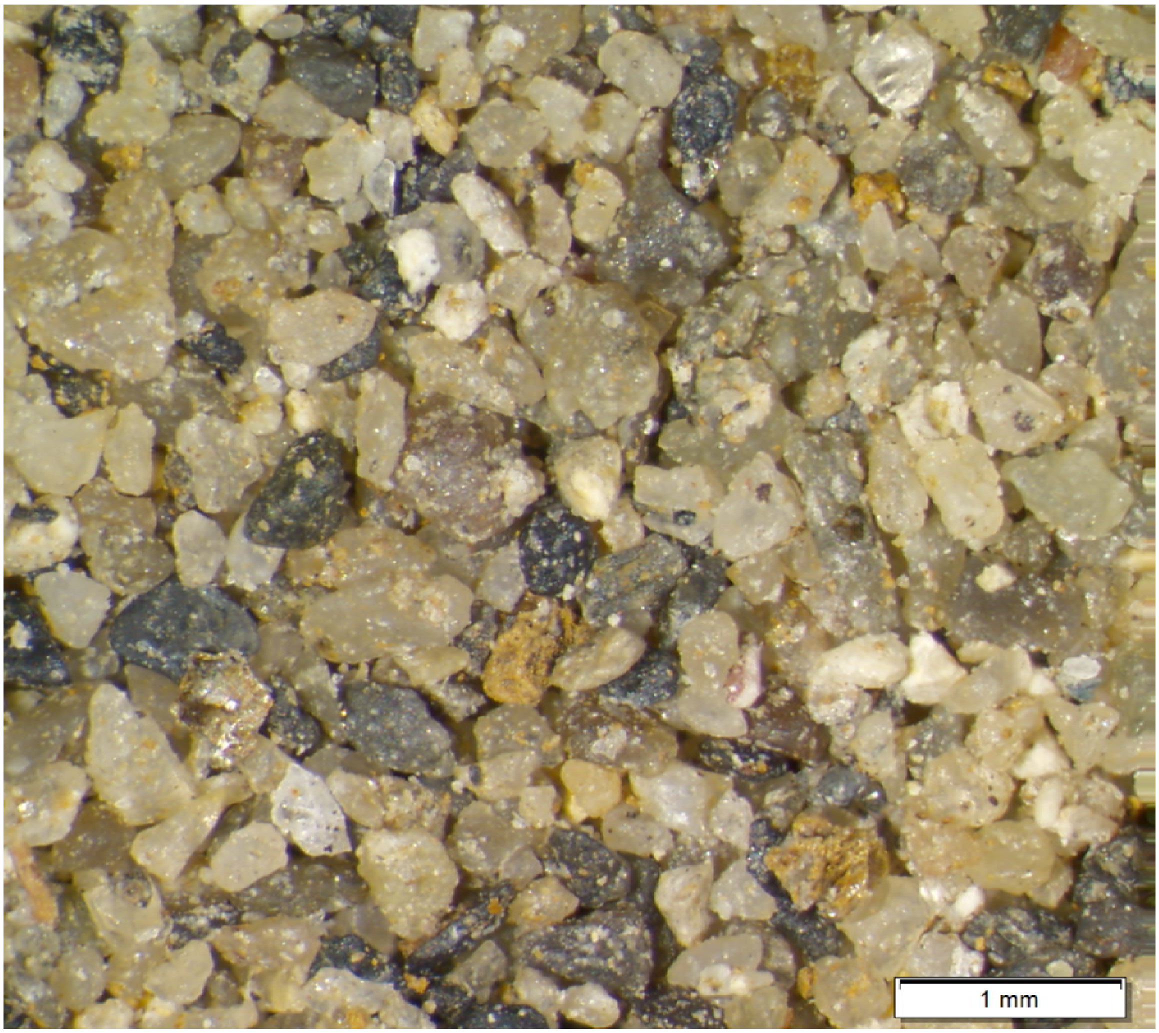
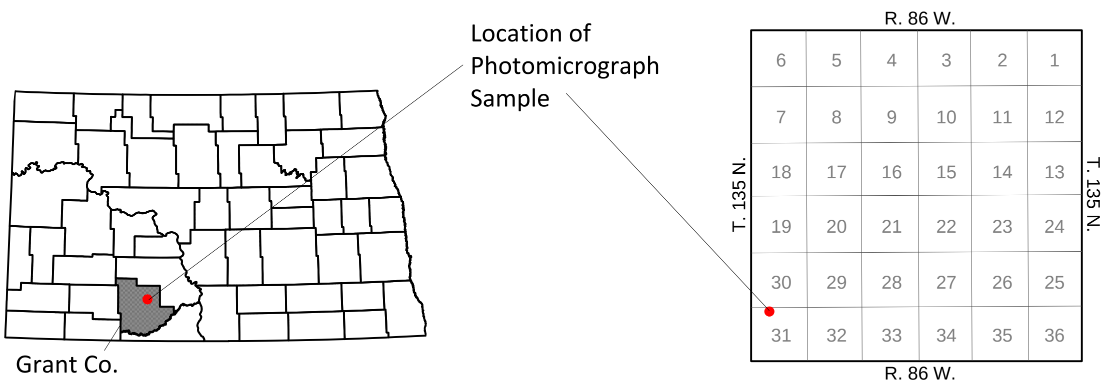


Figure 30. Photomicrograph (25x) of eolian sand from the Carson Dunes in northeastern Grant Co., North Dakota.



St. Anthony Dunes

NN1/4, SE1/4, 136-82-12

The St. Anthony Dunes are a low-relief dune field located directly south of St. Anthony in central Morton county, North Dakota. They cover an area of approximately nine square miles. These fine -to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

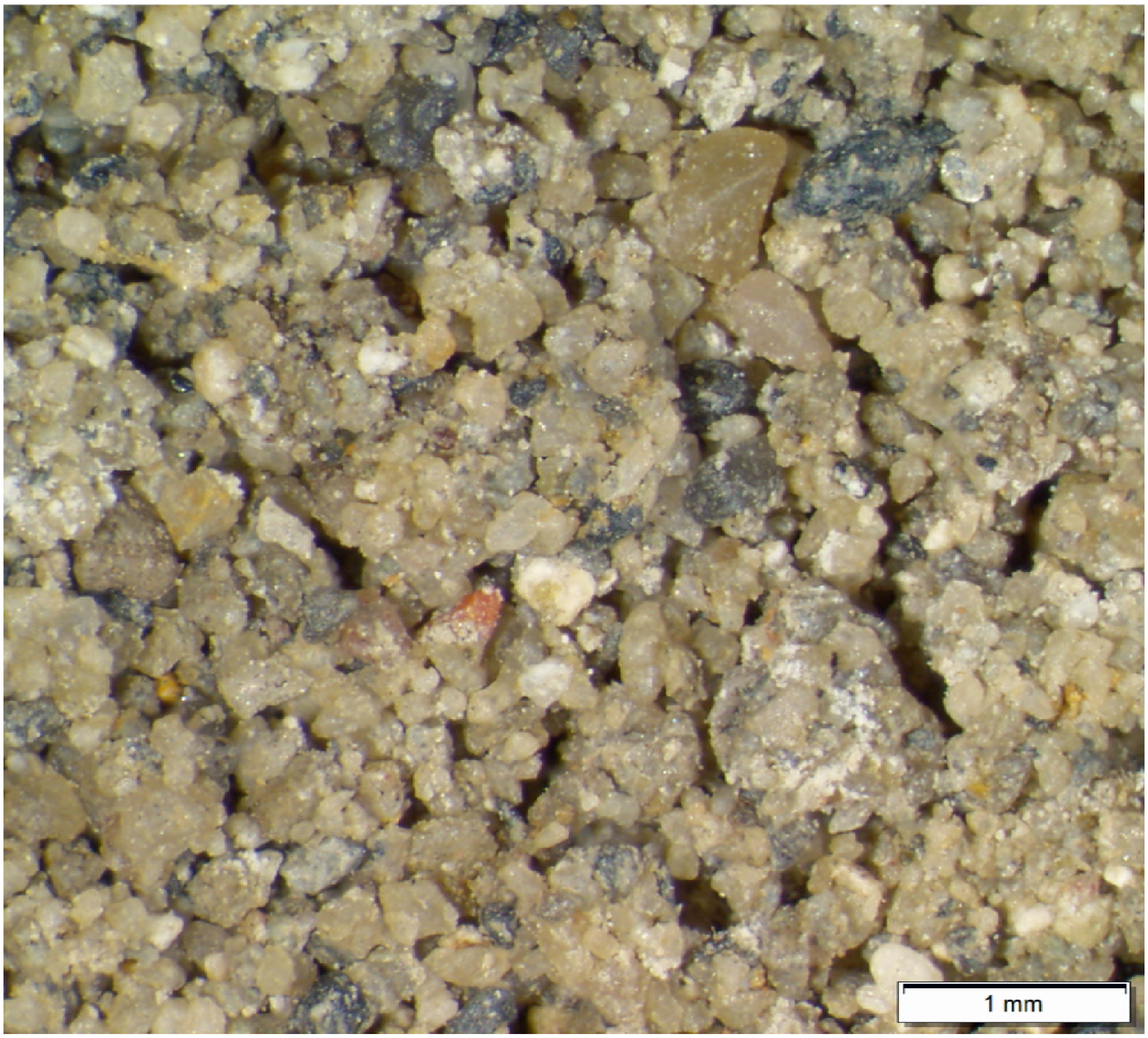
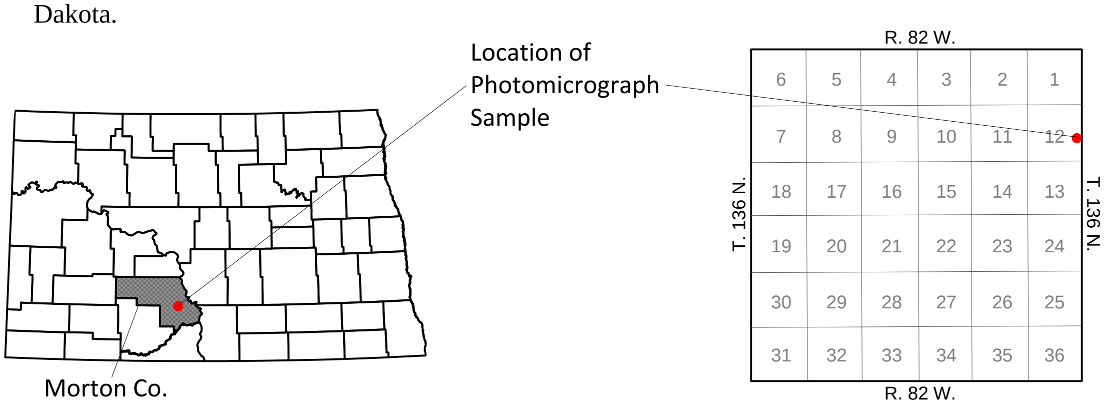


Figure 31. Photomicrograph (25x) of eolian sand from the St. Anthony Dunes in central Morton Co., North Dakota.

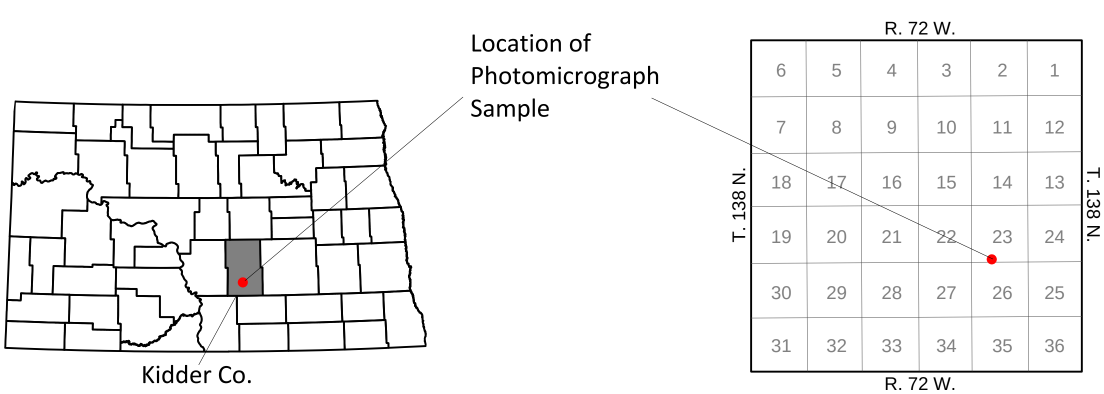


Dawson Dunes

SW1/4, NW1/4, 138-72-23

The Dawson Dunes are low-relief dunes located six miles south of Dawson in southern Kidder county, North Dakota. They cover an area of approximately 73 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

Figure 32. Photomicrograph (25x) of eolian sand from the Dawson Dunes in southern Kidder Co., North Dakota.



Tolna Dunes

NW1/4, NW1/4, 150-62-17

The Hamar-Tolna Dunes are a low-relief dune field located directly south of Hamar dominantly in northeastern Eddy county, North Dakota. They cover an area of approximately 40 square miles. These fine-to medium-grained, well-sorted (poorly graded) sands are middle-Holocene in age. Sand mineralogy consists of a variable composition of quartz, feldspar, and rock fragments consisting of shale, carbonates, and occasional detrital lignite.

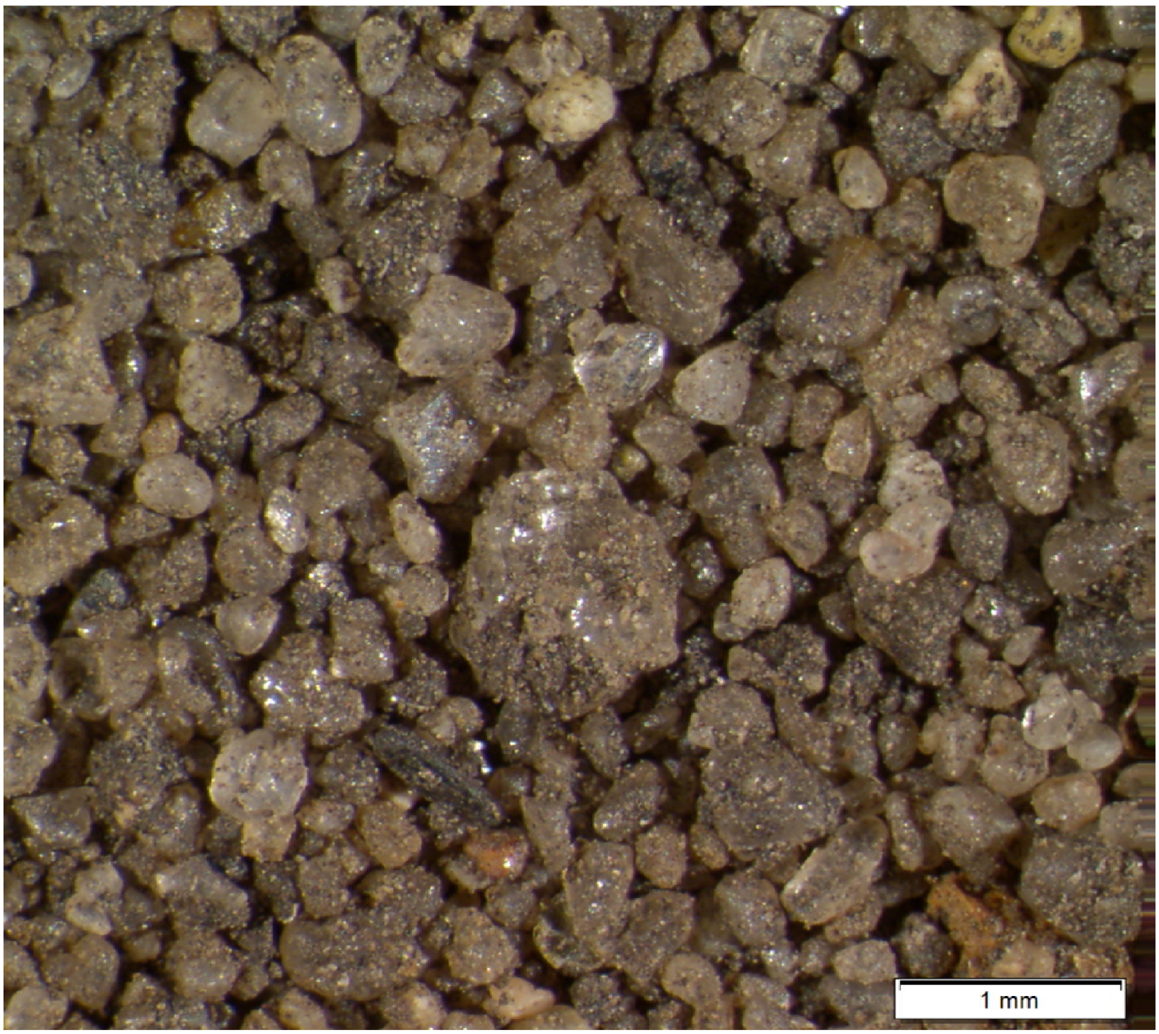
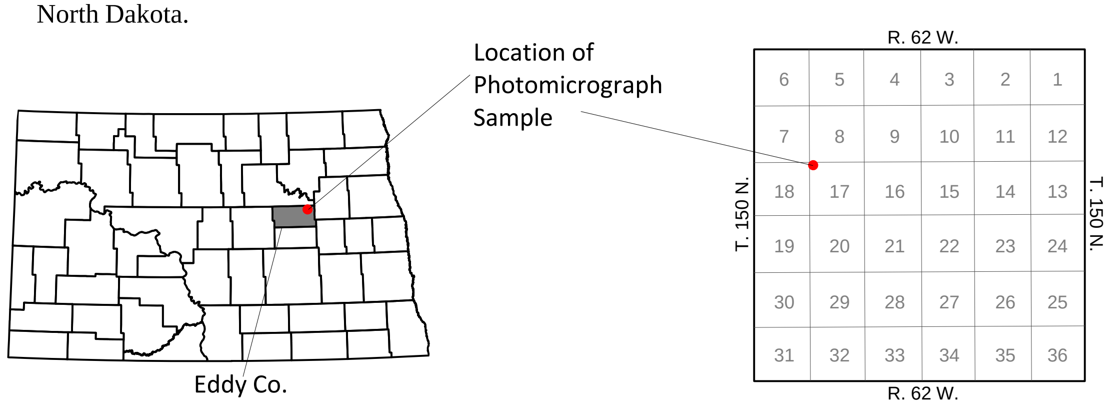


Figure 33. Photomicrograph (25x) of eolian sand from the Hamar-Tolna Dunes in northeastern Eddy Co., North Dakota.



SAMPLE COLLECTION METHODOLOGY

Description of Sample Collection

Samples of eolian sand were obtained primarily from two different sources during this investigation: 1) sand samples were collected as submitted from individual private landowners who reported appreciable amounts of sand occurring on their particular properties of interest that were further validated and re-sampled in the field, and 2) sand samples of opportunity and of pertinent geological origin, in this case known eolian sand deposits that were collected from high-relief dunes and low-relief dune fields by the NDGS during the conduct of field work on various unrelated projects across the state and for the deliberate collection of selected samples of geologic interest. 19 individual sand samples were collected from 17 of the 36 identified areas where eolian sand deposits occur. One of these samples was submitted by a private landowner in the Denbigh Dunes area (Figure 1). As cost was a factor in the testing program, the selection of samples for additional testing and characterization was based on several factors including: initial sand quality and character, location, and geological origin of the sampled deposits. As a result, two eolian sand samples from the Denbigh Dunes were submitted for detailed proppant testing and sedimentological characterization (Table 2) as this is the largest expanse of potential eolian sand resource in closest proximity to the heart of oil and gas development in the Bakken/Three Forks in the Williston Basin of North Dakota.

DESCRIPTON OF TESTING AND RESULTS

Selected eolian sand samples from the Denbigh Dunes were submitted for further testing and characterization (Table 2) in accordance with published and industry approved recommendations and specifications and included: particle size distribution (sieve analysis), percent clusters, grain morphology (sphericity and roundness), acid solubility, amount of silt and clay fines (turbidity), crush resistance, mineralogy, and material densities. Long-term conductivity testing was not performed due to budgetary constraints. All testing and analyses were completed by Stim-Lab, Inc., in Duncan, Oklahoma in June of 2011 (Table 3).

Sample Preparation

All samples submitted for testing were properly prepared for analysis by washing, drying, and disassociation. A percentage of the material removed during sample preparation constitutes the individual samples mass loss (commonly fines) and may be representative of the initial amount of material that can be expected to be removed (or lost) during the bulk volume washing process during production. Eolian sand sample No. 1 reported fines lost at 30%, and eolian sand sample No. 2 reported a fines loss of 4.9% (Table 4).

Particle Size Distribution – Textural (Sieve) Analysis

Sieve analyses are conducted on sediment samples in order to characterize the amounts of different sized sand grains within an individual sample. A series of stacked, wire-mesh sieves of standard sizes, are used to sieve each sand sample. Amounts of sands either being retained by the screen on each successively smaller opening sized sieve (% retained) or passing through the screen (% passing) are recorded and reported commonly as tabular data (Table 5) or in graphical form on a grain-size distribution diagram (Figure 2).

The resulting graph and grain-size curve conveys information on the amounts of particle sizes present and the degree of sorting or the variability (or lack thereof) of grains sizes. A well sorted sample (poorly graded in engineering parlance), will have much of the sample volume within or near the same or similar size classes (Table 6), resulting in a very steep curve on the grain size distribution diagram (Figures 34 & 35). All of the samples selected for testing were well sorted (poorly graded) sands (Appendix II). 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 gradual curve.

There are several slightly different types of sediment classification schemes, most notably, Modified Wentworth, Unified Soil Classification System, Association of State Highway and Transportation Officials, and several others. Generally these classifications vary in where they draw the boundaries between two different types of sediment (e.g. sand and gravel). For the purposes of detailed sedimentological characterization as related to geological processes, the Modified Wenworth system is used herein along with some brief engineering style summary statistics.

Table 2. Selected Eolian Sand Samples Submitted for Testing Location Summary

Sample No.	Sample ID (RI-110)	Location (T., R., Sec.)	County	Longitude	Latitude	Geologic Map Unit	Geologic Map Unit Description[1]
1	NDGS-GO-DD	156-77-6	McHenry	-100.62	48.36	Qod	Eolian Sand (Holocene)-Well-sorted, medium sand with obscure bedding; poorly developed paleosols common; as thick as 30 feet (10 meters); knobby topography consisting of inactive transverse or longitudinal dunes nearly obliterated by more recent blowouts.
2	NDGS-PL-JN	158-75-28	McHenry	-100.35	48.48	Qtou	Sand of the Oahe and Older Formations, Undivided (Holocene to Pliocene)-Eolian sand of the Oahe Formation, as thick as 10 feet, and sand of older formations with an undulating wind-scoured surface.

[1]Geologic map unit and map unit descriptions as initially documented in the Geologic Map of North Dakota (Clayton et. al., 1980).

Table 3. Proppant Testing Analytical Summary - Selected Eolian Sands in North Dakota

Sample No.	Tested Size Cut	Crush Resistance (K-Value)	Acid Solubility (%)	Sphericity	Roundness	ISO Mean Particle Dia. (mm)	Median Particle Dia. (mm)	Turbidity (FTU)	% Clusters	Bulk Density (g/cm^3)	Bulk Density (pcf)	Specific Gravity (g/cm^3)
1	40/70	<2K	16.6	0.6	0.5	0.239	0.236	85	~1/100	1.23	76.8	2.58
2	30/50	5K	6.4	0.6	0.5	0.428	0.418	18	NIFC	1.44	89.9	2.65

K-Value is defined as the highest stress level which proppant generates no more than 10% crushed material, rounded down to the nearest 1,000 psi.

FTU = Formazin Turbidity Unit.

NIFC = No clusters observed in field of count.

pcf = pounds per cubic foot.

Table 4. Calculated % Fines Loss on Sample Prepatory Wash.

No.	Sample ID	Initial Weight (g)	Weight after Wash (g)	Weight Loss (g)	Loss (%)	Geologic Unit
1	NDGS-GO-DD	11422.46	7994.24	3428.2	30.0	Qod
2	NDGS-PL-JN	14258.92	13559.52	699.4	4.9	Qtou

GO: Geologic Origin, PL: Private Landowner

Table 5. Bulk Composite Sample Sieve Analysis Results (Weight Percent Retained).

Sample No.	1	2
U.S. Standard Sieve No.	NDGS-GO-DD	NDGS-PL-JN
6	0.0	0.0
8	0.0	0.0
10	0.0	0.0
12	0.0	0.0
14	0.0	0.0
16	0.0	0.0
18	0.0	0.1
20	0.0	0.4
25	0.0	1.6
30	0.1	4.0
35	0.1	7.6
40	0.1	9.8
45	0.2	12.7
50	0.3	12.6
60	1.2	11.1
70	4.6	10.5
80	8.5	8.4
100	14.1	8.2
120	18.1	6.0
140	20.4	4.4
170	13.4	1.9
200	10.7	0.6
230	4.9	0.0
270	2.2	0.0
325	0.8	0.0
pan	0.6	0.0
Total	100.0	100.0

Table 6.
Selected Most Abundant Sized Sample Sieve Analysis Results (Weight Percent Retained)

Sample No.	1	2
U.S. Standard Sieve No.	40/70	30/50
20	0.0	0.0
25	0.0	0.0
30	0.0	1.2
35	0.0	20.0
40	0.0	24.5
45	0.0	30.3
50	0.2	23.6
60	20.1	0.5
70	75.5	0.0
80	3.9	0.0
100	0.1	0.0
pan	0.1	0.0
Total	99.9	100.1
In-Size	95.8	98.3

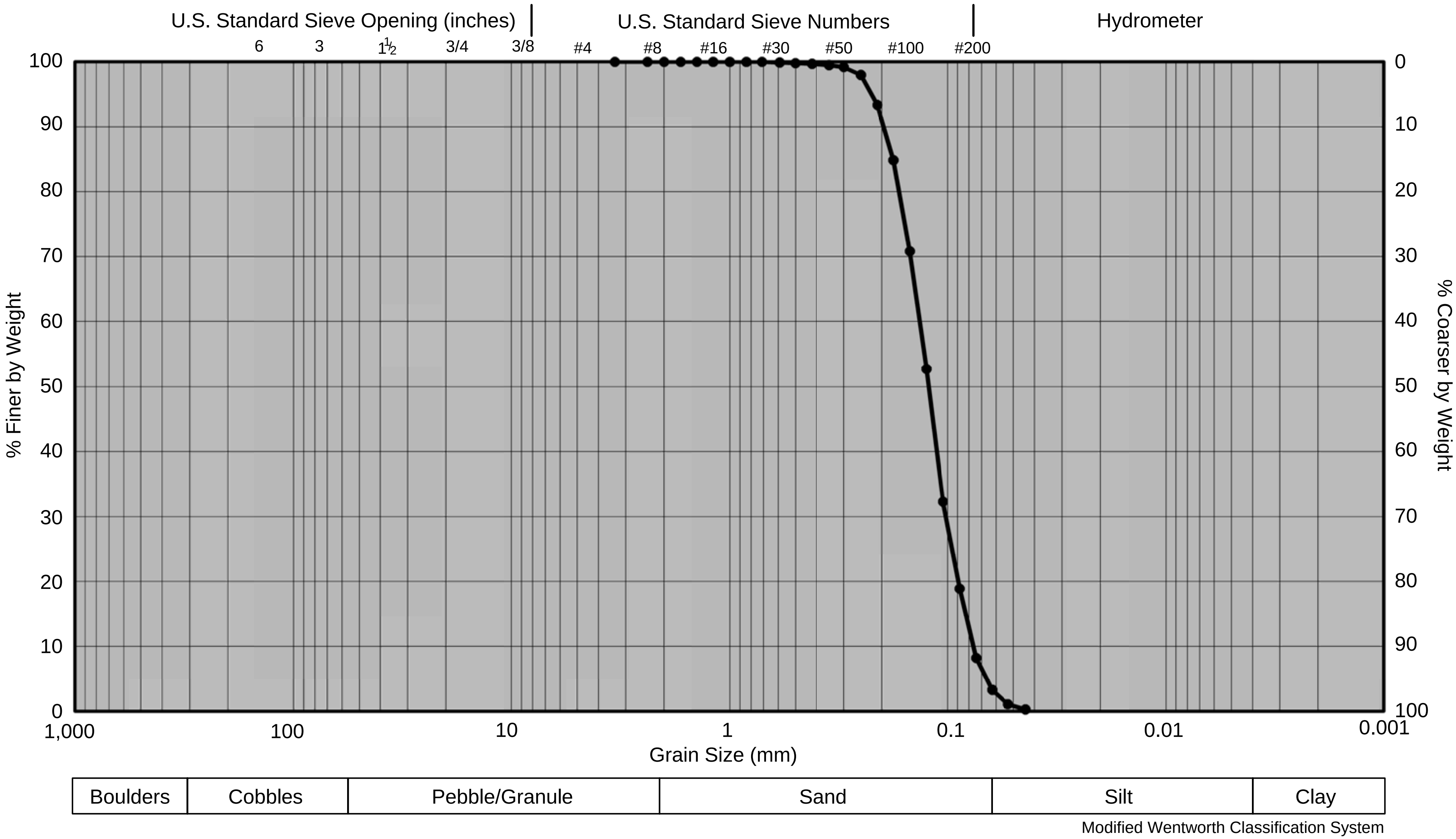


Figure 34. Bulk Sample Grain-Size Distribution Diagram for Sample No. 1 - Qod.

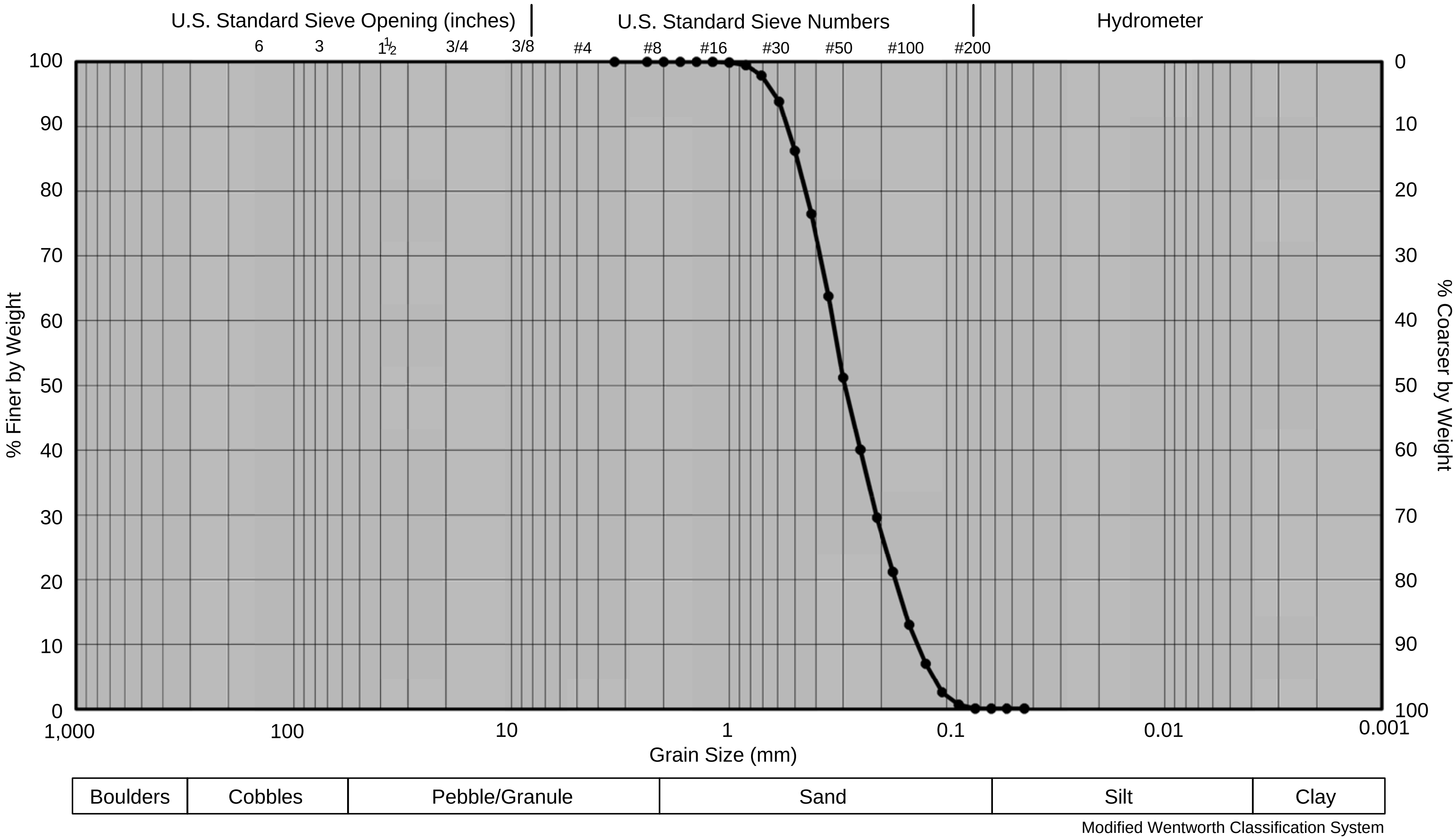


Figure 35. Bulk Sample Grain-Size Distribution Diagram for Sample No. 2 - Qtou.

Both of the eolian sand samples selected for further testing and characterization as potential proppants fell into the grain size ranges for classification as a “Sand” according to the Modified Wentworth classification scheme (Figures 36 & 37) and can be further characterized as well sorted (poorly graded) to very well sorted, fine to medium grained sands. Sample No. 1 had its most abundant amount in the 70/140 size range, whereas Sample No. had its most abundant sand size amount in the 40/70 size range (Table 7).

Additional engineering statistical analyses can also be completed on data generated in a grain-size distribution diagram, which can be used to quantitatively compare individual samples for potential engineering applications. 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 8).

% Clusters

The amount of sample grains that tend to be aggregated together in clusters is estimated by visual inspection of an individual sample under the microscope at 10x to 20x magnification. Clusters may be problematic in a particular proppant depending on the size of the clusters and type of geochemical cement that may be holding the individual grains together. Sand to be used as a proppant is recommended to have less than 1% by count (<1/100) of clusters within individual sand grains (API, 1995a).

Sample No. 1 had sand grain clusters reported at approximately 1% by visual-manual microscopic inspection methods. Sample No. 2 reported no sand grain clusters observed (Table 2) in the field of count (NIFC).

Sand Grain Morphology (Sphericity and Roundness)

Individual sand grain sphericity and roundness are two shape factors that are evaluated when characterizing a sand for potential use as a proppant and can be qualitatively observed through standard 40x magnification photomicrographs (Figure 38). Sphericity refers to how closely a particular grain of sand resembles that of a sphere and roundness refers to the shapes of the corners of an individual sand grain. A sand with high sphericity and roundness is desirable. Recommended sphericity and roundness values of 0.6 or greater are desirable for frac sand, with values of 0.7 or greater for proppants characterized as being of high-strength (API, 1995a and b). Both samples tested had sphericity and roundness values (Table 2) reported at 0.6 and 0.5, respectively (Figure 39).

Acid Solubility

The amount of particular sand that is soluble in a 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 no greater than 2% (by weight) of 30/50 or larger sized sand and no greater than 3% (by weight) of 40/70 or smaller sized sand, to be used as proppant be soluble in a 12:3 hydrochloric (HCL) to hydrofluoric (HF) acid solution. None of the samples tested were

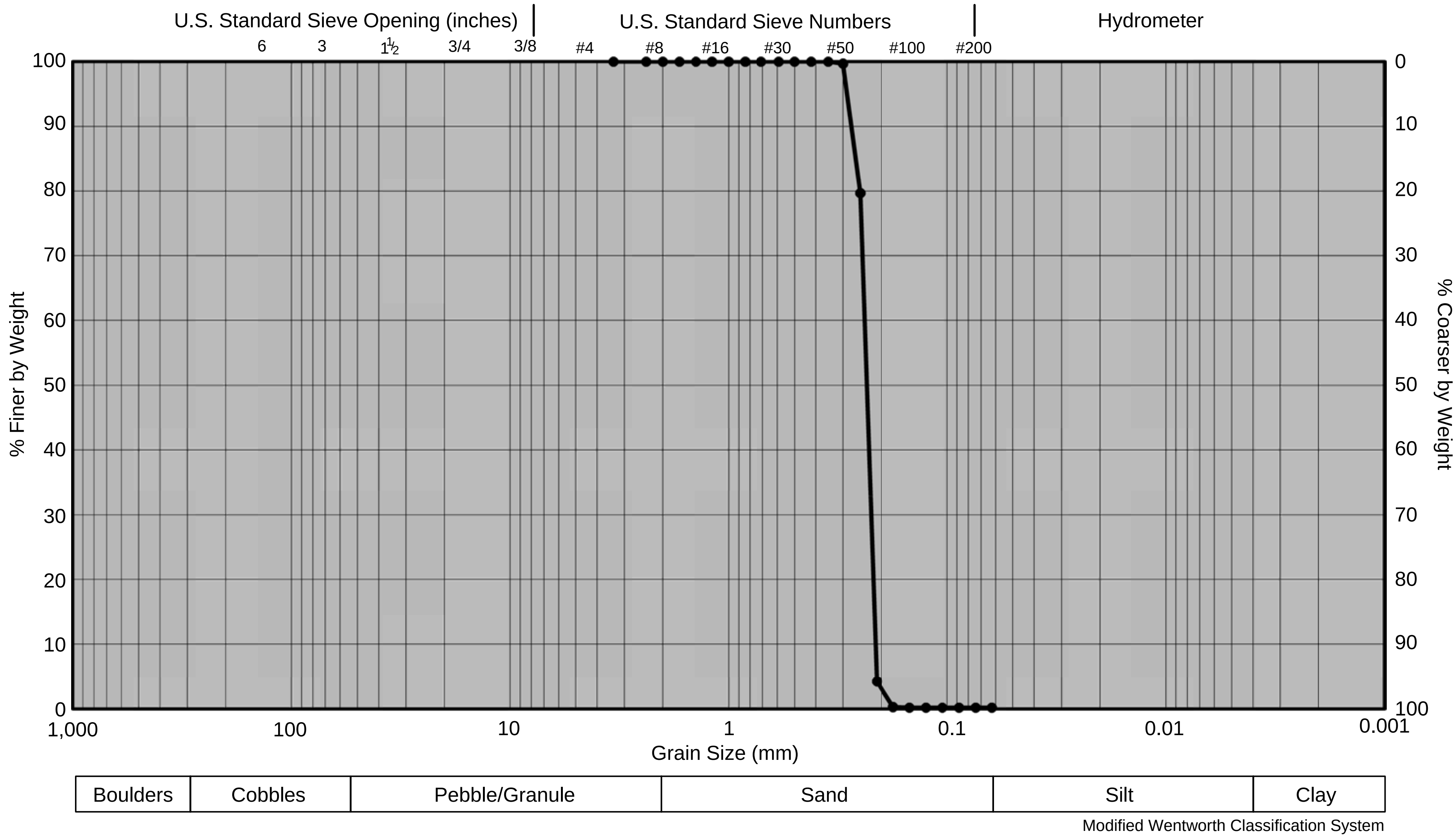


Figure 36. Grain size distribution diagram for Sample No. 1 - Qtou 40/70 Cut.

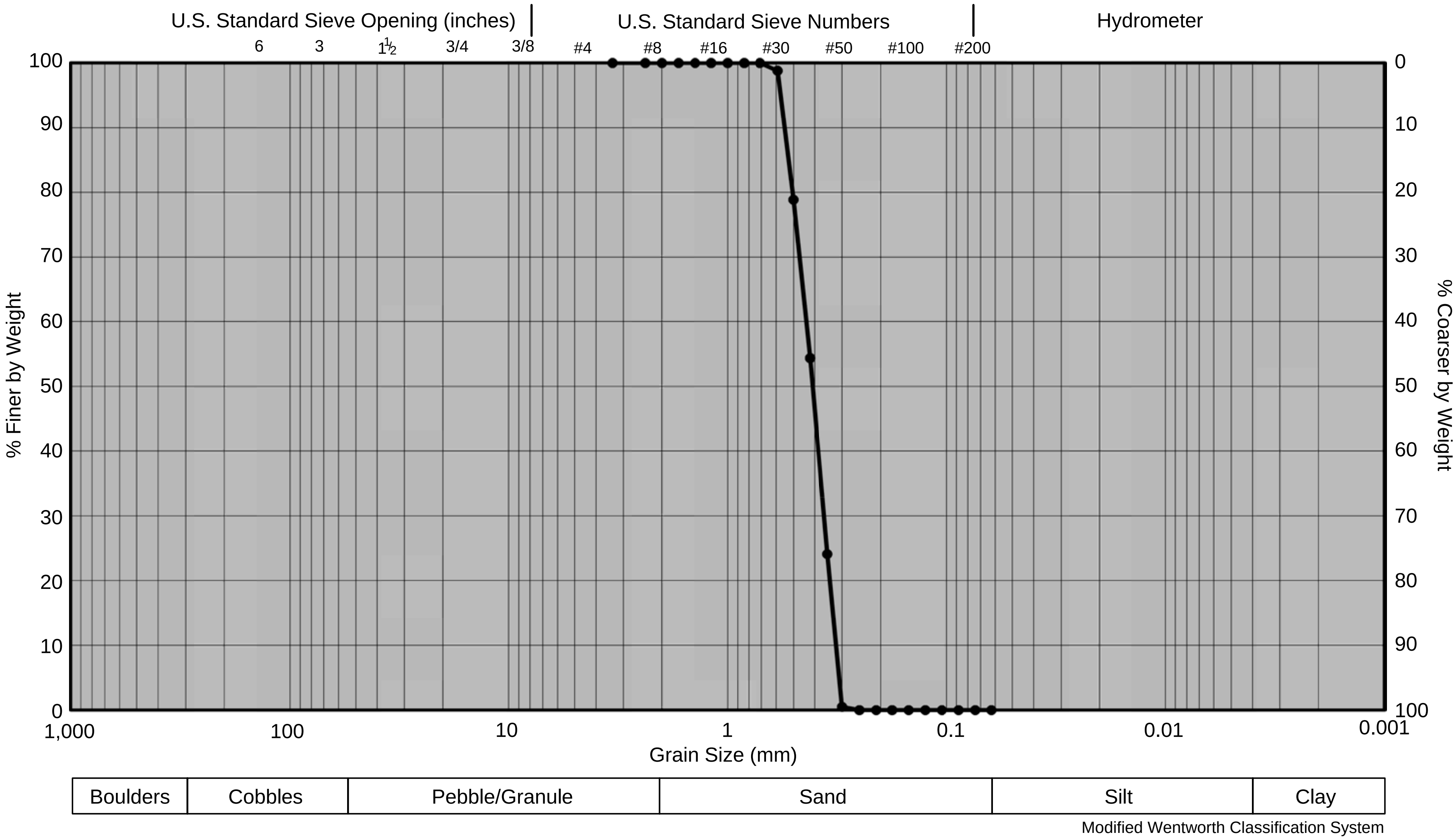


Figure 37. Grain size distribution diagram for Sample No. 2 - Qtou 30/50 Cut.

Table 7. Bulk Composite Sample Sieve Analysis Results (Percent In-Size).

Sample No.\ID	1	2
Size Class	NDGS-GO-DD	NDGS-PL-JN
6/12	0.0	0.0
8/16	0.0	0.0
12/20	0.1	0.6
16/30	0.1	6.2
20/40	0.2	23.1
30/50	0.6	42.7
40/70	6.2	46.8
70/140	61.0	27.0

Table 8. Grain-Size Distribution Engineering Statistics Summary.

Sample No.	Sample Type	ISO Mean Particle Dia. (mm)	Median Particle Dia. d_{50} (mm)	Graphical d_{90} (mm)	Graphical d_{84} (mm)	Standard Deviation[1]	Geologic Unit
1	Composite	0.135	0.134	0.19	0.17	1.27	Qod
	40/70	0.239	0.236	0.28	0.18	0.76	
2	Composite	0.268	0.283	0.55	0.48	1.70	Qtou
	30/50	0.428	0.418	0.53	0.51	1.22	

[1] Standard Deviation calculated as d_{84}/d_{50}

Sample No. 1 Qod 40/70

Sample No. 2 Qtou   30/50

Figure 38. Standard (40x) photomicrographs of individual selected sand samples in North Dakota tested for use as proppants for hydraulic fracturing of oil & gas wells.

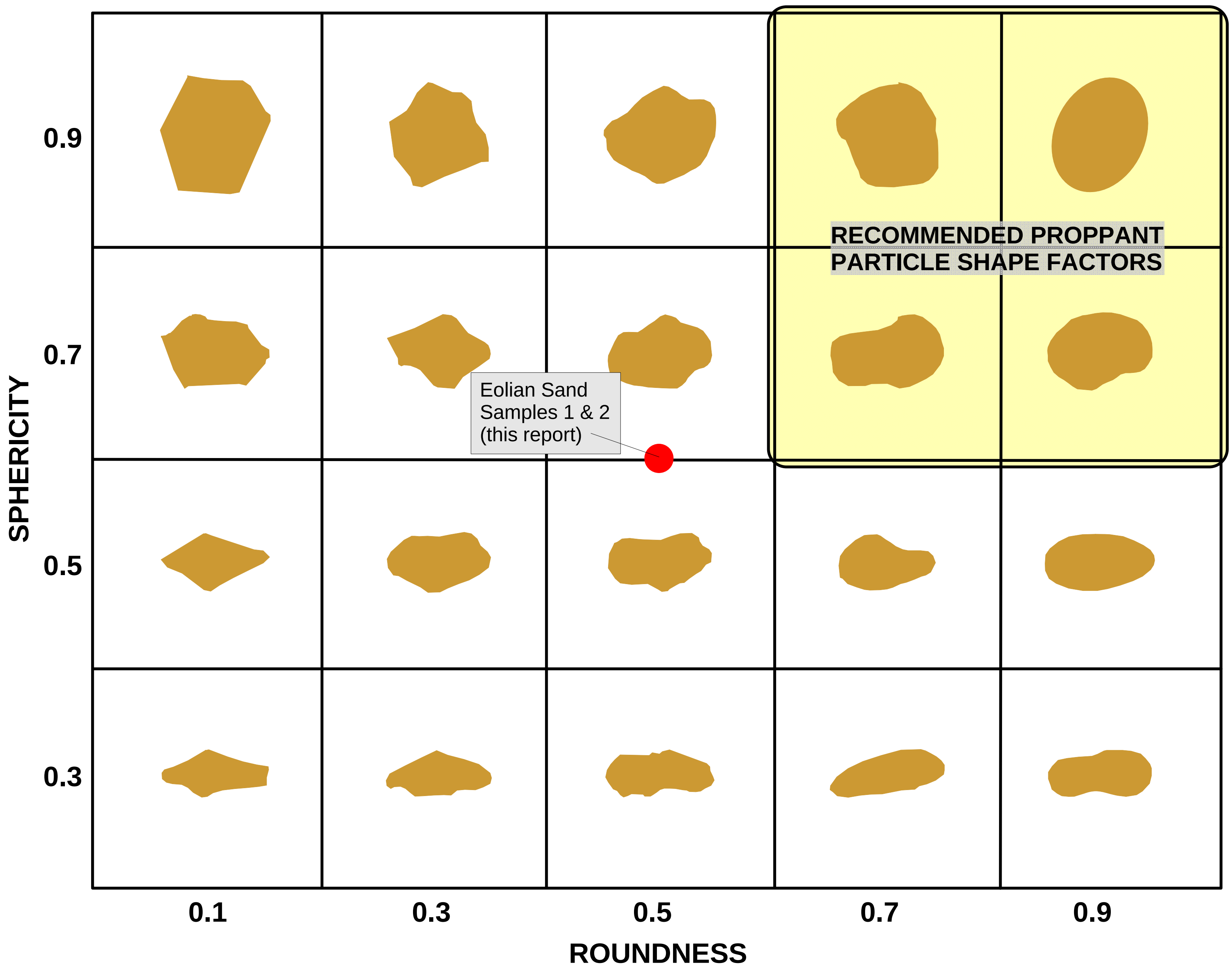


Figure 39. Sphericity and roundness chart displaying the range of recommended proppant particle shape factors and values for selected eolian sand samples tested from sand deposits in North Dakota.

below the recommended acid solubility of 2% and 3% or less (Figure 40). Acid solubilities of 16.6% and 6.4% were reported for Samples No. 1 and 2, respectively.

Silt and Clay Fines Testing (Turbidity)

Turbidity measures an optical property of a water sample with a particular amount of suspended sediment contained within it. It is commonly used to determine the percentage amount of fine materials (e.g. silts and clays) that may be present within a particular sample. With respect to a sand sample to be used as potential proppant, turbidity is a method to measure the amount of associated fines contained within a particular sand sample. It can be used to determine what sand sources may need additional prepatory steps (e.g. washing) during initial processing of the raw mined product into an eventual final frac-sand product. Turbidity is measured and commonly reported in Formazin Turbidity Units (FTU), which are standard suspensions where turbidity values are determined and reported against. The recommended limit of tested frac sand would be less than 250 FTU. All the samples tested for characterization for use as natural proppants were well below the recommended limit of 250 FTU at 85 FTU for Sample No. 1 and 18 FTU for Sample No. 2 (Figure 41).

Crush Resistance

Since the composition of sands can be quite variable (remembering that sand is in fact a size term that does not reflect the compositional or mineralogical character of a particular sample), the resultant strengths of sands are also highly variable. The measuring of the amount of fine-grained material generated during the subjection of a given sand sample (within a specified size range) to a pre-determined amount of stress or load is done by a crush resistance test. Crush resistance testing was performed on both of the two selected eolian sand samples that were submitted for testing and characterization (Figure 42). Samples were subjected to one set of three predetermined stresses, depending on the size range of the tested samples, and a resultant K-value was determined. A K-value is determined from the amount of crushed fines generated at a particular applied stress value and is defined as the highest stress level that will generate no more than 10% crushed material (rounded down to the nearest 1,000 psi).

Sample No. 1 was subjected to a stress level set of 2,000, 3,000, and 4,000 psi and generated K-values of <2K. Sample No. 2 was subjected to a stress level set of 4,000, 5,000, and 6,000 psi and generated a K-value of 5K (Table 9). Representative Ottawa "white" sands commonly generate K-values around 7K. It appears that the selected sands tested could find use in the hydraulic fracturing of oil and gas wells in reservoir applications where the fracture closure stresses are less than 5,000 psi.

Mineralogy (X-Ray Diffraction)

Bulk sample geochemistry was analyzed through X-Ray Diffraction (XRD) on Sample No. 1 (Table 10). XRD analysis is commonly used to determine the mineralogy of fine-grained sediments, particularly clays (Poppe et. al. 2001). Generally, mineralogical composition is similar in character to the surrounding sediments from which these dune sand originate. Sample No. 1, which was collected from one of the larger dunes in the Denbigh Dunes area, consisted of 85% silicates, 14% clays and

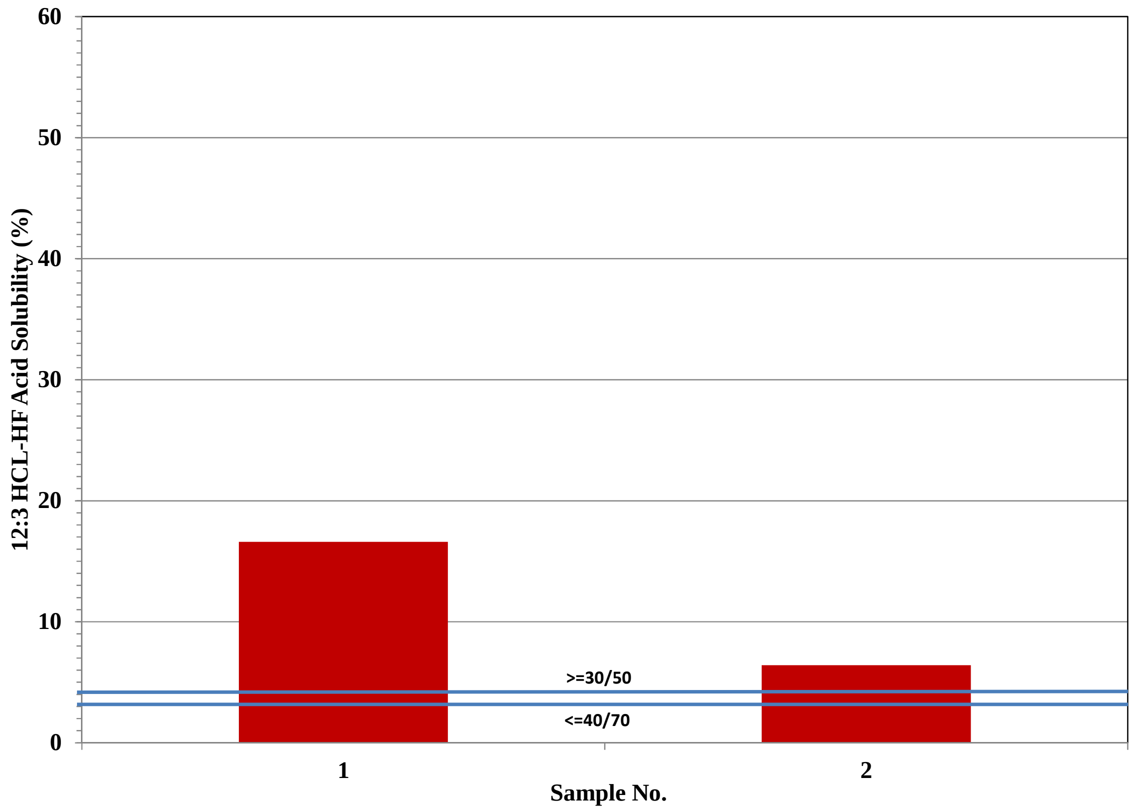


Figure 40. Comparison of HCL:HF Acid solubility results for selected eolian sand samples.

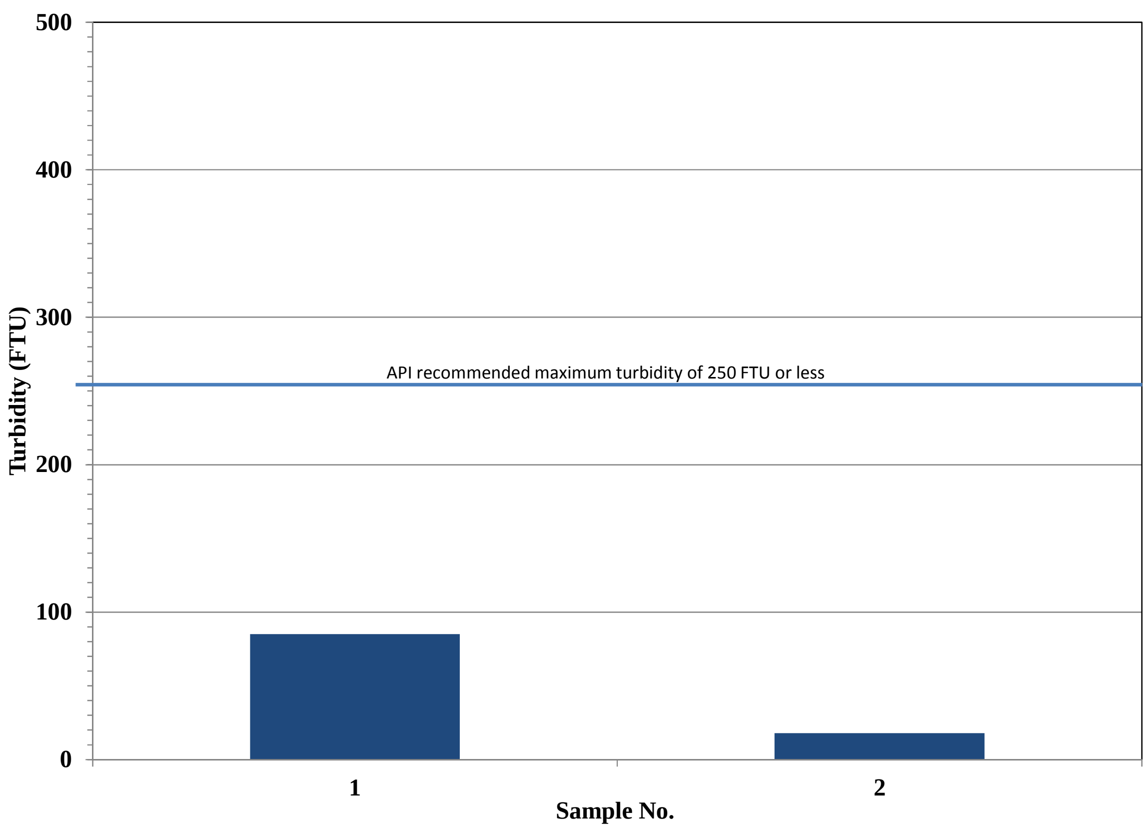


Figure 41. Comparison of turbidity results for selected eolian sand samples.

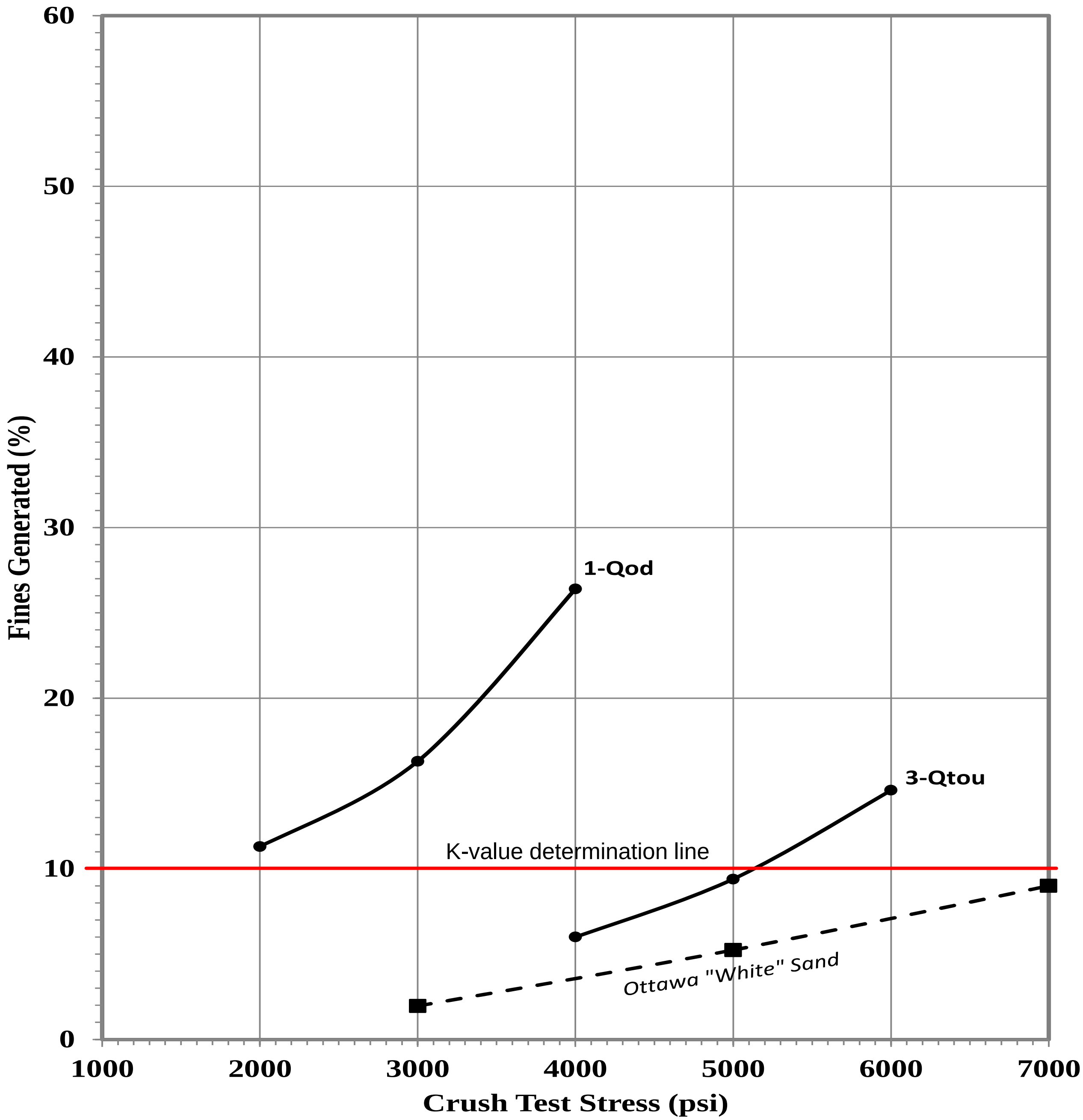


Figure 42. Crush test stress versus fines generated curves for selected eolian sand samples from North Dakota: Sample No. 1 - Windblown Sand (Qod) from the Denbigh Dunes area in McHenry County , Sample No. 2 - Wind -blown Sand (Qtou) of the Denbigh Dunes area in northeastern McHenry County.

Table 9. Crush Resistance Testing Summary

Sample No.	1-Qod	2-Qtou
Tested Stress (psi)	% Fines Generated on Crush	
2,000	11.3	--
3,000	16.3	--
4,000	26.4	6.0
5,000	--	9.4
6,000	--	14.6
K-Value	<2K	5K

Table 10. Detailed X-Ray Diffraction Mineralogy Analyses on Selected Eolian Sand Samples (Clay and Bulk).

Sample No.	Quartz (%)	Plagioclase (%)	K-Feldspar (%)	Calcite (%)	Dolomite (%)	Hornblende (%)	Micas (%)	Iron Oxides (%)	Pyrite (%)	Zeolites (%)	Total Clays (%)	Illite (%)	Smectite (%)	Chlorite (%)	Kaolinite (%)	Geologic Unit
1	57	15	12	2	4	1	--	--	1	--	8	3	5	tr.	tr.	Qod

carbonates, and 1% iron in the form of pyrite and other iron oxides (Figure 43). In comparison, Ottawa “white” silica sands are commonly 99% quartz sand. Silicate minerals reported included: Quartz, Plagioclase, K-Felspar, and Hornblende. Quartz sand was the major silicate mineralogical component at 57% followed by lower amounts of Feldspar ranging 27% with lesser amounts of Hornblende and Pyrite at 1% (Figure 44). In terms of comparative sedimentary petrology, a silicate composition like this would be consistent with that of a lithic arkose. Carbonate minerals reported included Calcite at 2% and Dolomite at 4%. Total clay minerals of 8% reported included: Illite, Smectite, Chlorite, and Kaolinite.

Bulk Density

The bulk density of a proppant describes the mass that fills a unit volume and includes both the proppant and the void space (i.e. porosity) in the sample and is commonly used for determining the mass of proppants required to fill fractures, a storage vessel, or in completing general volume estimates. The bulk density of selected eolian sand tested in North Dakota for potential use as a proppant (Figure 44) ranged from 1.23 to 1.44 g/cm^3.

Specific Gravity

The specific gravity (i.e. apparent density) of a sand is another measure of potential proppant density that *includes* the void or pore space that is inaccessible to the testing fluid, which is a low-viscosity oil that wets the particle pore spaces. The specific gravity of selected sands tested in North Dakota for use as proppant (Figure 44) ranged from 2.58 to 2.65 grams per cubic centimeter (g/cm^3). The specific gravity of quartz sand on average is 2.65 g/cm^3 (Olhoeft and Johnson, 1989).

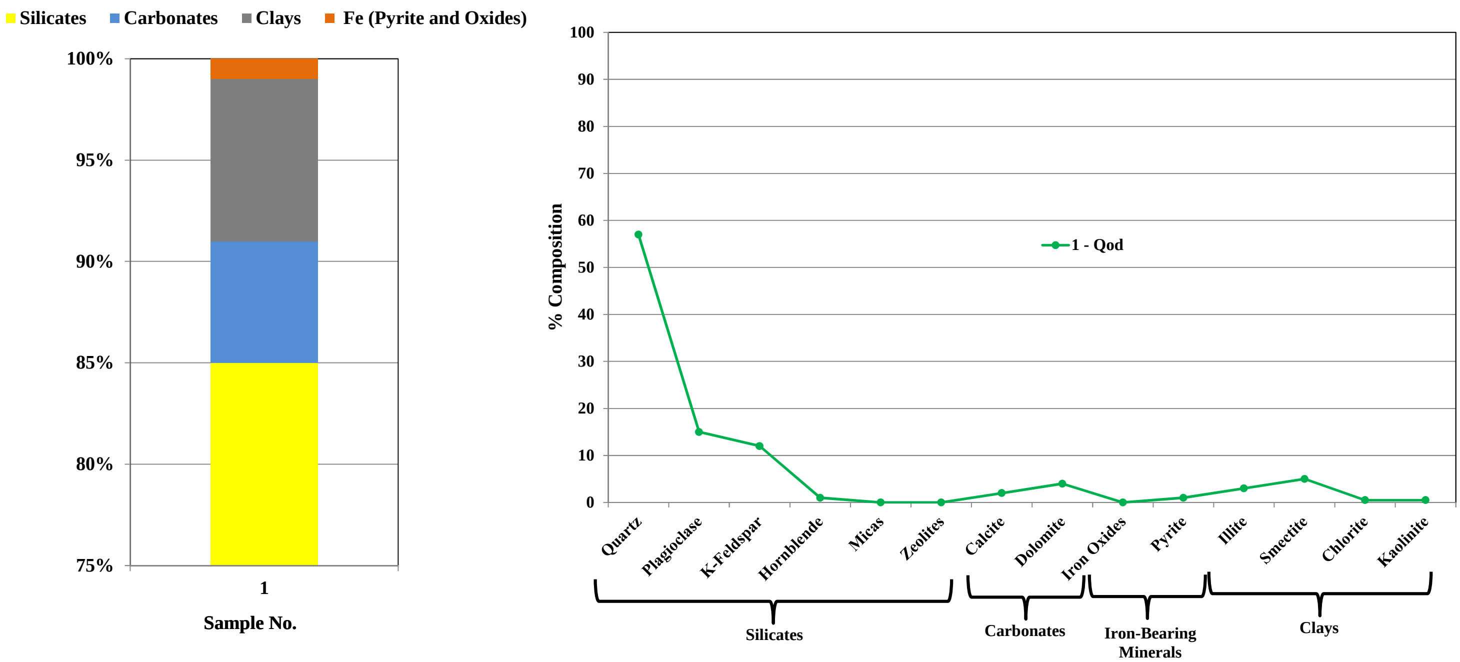


Figure 43. Bulk and Detailed X-Ray Diffraction (XRD) mineralogical analyses for selected eolian sand deposits in North Dakota.

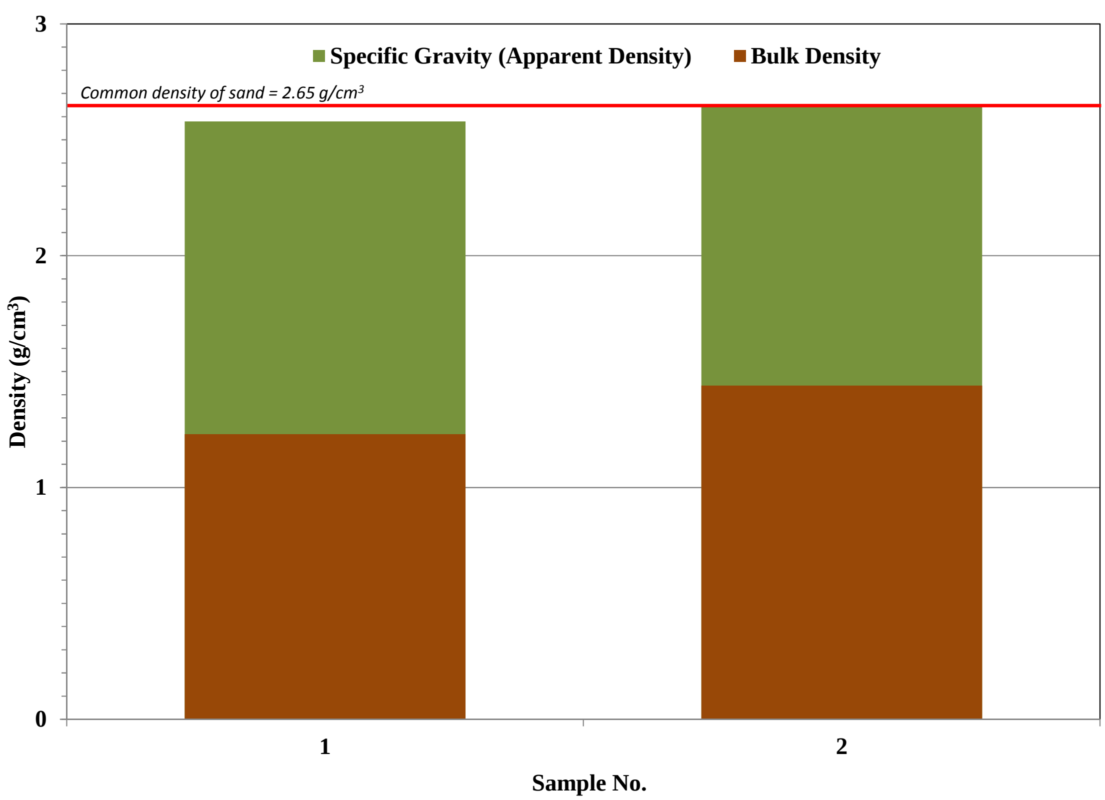


Figure 44. Comparison of Specific Gravity (apparent density) and Bulk Density values for selected eolian sand deposits.

CONCLUSIONS

Selected North Dakota eolian sand deposits were sampled and tested for potential use as natural sand proppants in the hydraulic fracturing of oil and gas wells in the Williston Basin during the 2009 to 2011 biennium and are currently being re-evaluated during this, the 2017 to 2019 biennium. Previous materials testing and sediment characterization indicated that North Dakota's sand resources are of a condition and quality that approached the extreme quality specifications of industry standards at the time, However, since they are of a lesser overall quality in direct comparison with other extreme high-quality domestic sand sources currently being utilized as proppant in the U.S., such as Ottawa "white" and the lesser quality Brady "brown" type sands which are texturally and mineralogically more mature sediments, significant processing and material refinement would still be required to bring deposits of marginal quality up to applicable extreme high-quality standards and specifications. The recent oil and gas industry trend towards a relaxation of the need for extreme-quality natural sand proppants that are transported from a distant source in lieu of an adequate local or regional natural sand proppant source has the potential to render North Dakota's abundant sand deposits viable. This may be made possible through the deposit refinement process during initial extraction and production through an acceptance of significant initial volume losses or through other material enhancement processes (such as resin coating or blending with ceramic proppants), or enhancements in other areas of the hydraulic fracturing design formula. The information contained in this report will also find use in the continued characterization of North Dakota's sand resources for use in other industrial applications.

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APPENDIX I. Testing Specifications and Recommendations for Natural Sand Proppants

Provided below is a summary of the current testing specifications and recommendations for natural sand proppants characterized for use in the hydraulic fracturing of oil and gas wells. These specifications and recommendations are summarized from current recommended specifications published by the International Organization for Standardization (ISO), the American National Standards Institute (ANSI), the American Petroleum Institute (API), and current industrial practice.

Grain-Size Distribution (Sieve Analysis)

It is recommended that a minimum of 90% of the tested sand fall between the designated sieve sizes, meaning that for a 30/50 sized sand, 90% would pass the coarser primary sieve (i.e. the No. 30 sieve), and be retained on the finer secondary sieve selected (i.e. the No. 50 sieve).

Sphericity and Roundness (Particle Shape Factors)

Natural sands used in the hydraulic fracturing of oil and gas wells are recommended to have particle sphericity and roundness values of 0.6 or greater as determined by visual-manual comparison of sand grains under the microscope or through evaluation of suitable photomicrographs.

Acid Solubility

Evaluation of the solubility of sand in a 12-3 hydrochloric (HCL)-hydrofluoric (HF) acid gives a measure of the amount of undesirable and potentially deleterious “contaminants” such as: carbonates, feldspars, iron oxides, and clays that are found in the sand. It is recommended that for sands sized in the range from 6/12 to 30/50 contain no more than two percent (by weight) HCL-HF soluble constituents, and for sands sized in the range from 40/70 to 70/140 contain no more than three percent (by weight) HCL-HF soluble constituents.

Turbidity

The amount of suspended clay, silt, or finely divided organic sediment in water is a measure of a sand samples turbidity. It is recommended that natural sands used as proppants have turbidity values no greater than 250 Formazin Turbidity Units (FTU).

Crush Resistance

A sand samples resistance to crushing is an important characteristic in comparing different types of proppant sand and is performed by subjecting a particular sand sample to a predetermined level of stress and measuring (in percent by weight) the amount of crushed material (i.e. fines) generated in a two inch diameter piston-crushing cell. A crush resistance K-value is determined as the highest stress level at which no more than 10% crushed material is generated (rounded down to the nearest 1,000 psi). For a natural sand proppant sized at 6/12 it is recommended that no more than 20% of fines are generated, when subjected to an applied stress of 2,000 pounds per square inch (psi). For a natural sand proppant sized at 8/16 it is recommended that no more than 18% of fines are generated, when subjected to an applied stress of 2,000 psi. For a natural sand proppant sized at 12/20 it is recommended that no more than 16% of fines are generated, when subjected to an applied stress of 3,000 psi. For a natural sand proppant sized at 16/30 it is recommended that no more than 14% of fines are generated, when subjected to an applied stress of 3,000 psi. For a natural sand proppant sized at 20/40 it is recommended that no more than 14% of fines are generated, when subjected to an applied stress of 4,000 psi. For a natural sand proppant sized at 30/50 it is recommended that no more than 10% fines are generated, when subjected to an applied stress of 4,000 psi. For a natural sand proppant sized at 40/70 it is recommended that no more than 8% fines are generated, when subjected to an applied stress of 5,000 psi. For a natural sand proppant sized at 70/140 it is recommended that no more than 6% fines be generated, when subjected to an applied stress of 5,000 psi.

Mineralogy

In order to provide an understanding of overall mineralogical character, it is recommended that a qualitative mineralogical analysis be conducted, by X-ray diffraction (XRD) methods, on a representative sample of sand that is either being used or being evaluated for use as a natural sand proppant. Evaluation of relative peak heights should be used to estimate the amount of clays present in addition to reporting any minerals found at levels above about 1 percent.

APPENDIX II. Grain-Size Distribution Curves for Eolian Sands

Provided in this appendix is a set of 20 grain-size distribution curves and associated testing data generated from additional materials testing work completed by the North Dakota Department of Transportation's Materials and Research Division in May, 2018. Gradational analysis consisting of combined sieve and hydrometer analyses were performed in accordance with applicable American Association of State Highway and Transportation Officials (AASHTO) standards.

Textural analysis indicates that tested samples consist of 89 percent sand, seven percent silt, and four percent clay on average. Sand percentages ranged from 48-98 percent. However, the sample collected from the high-dunes area within the Brampton dunes in southwestern Sargent County contained a higher silt percentage of 49.4 percent. The average sand percentage in all the other eolian sand areas averaged at a more uniform 91 percent, with corresponding silt and clay percentages at five and four percent, respectively (Figure A-II-1).

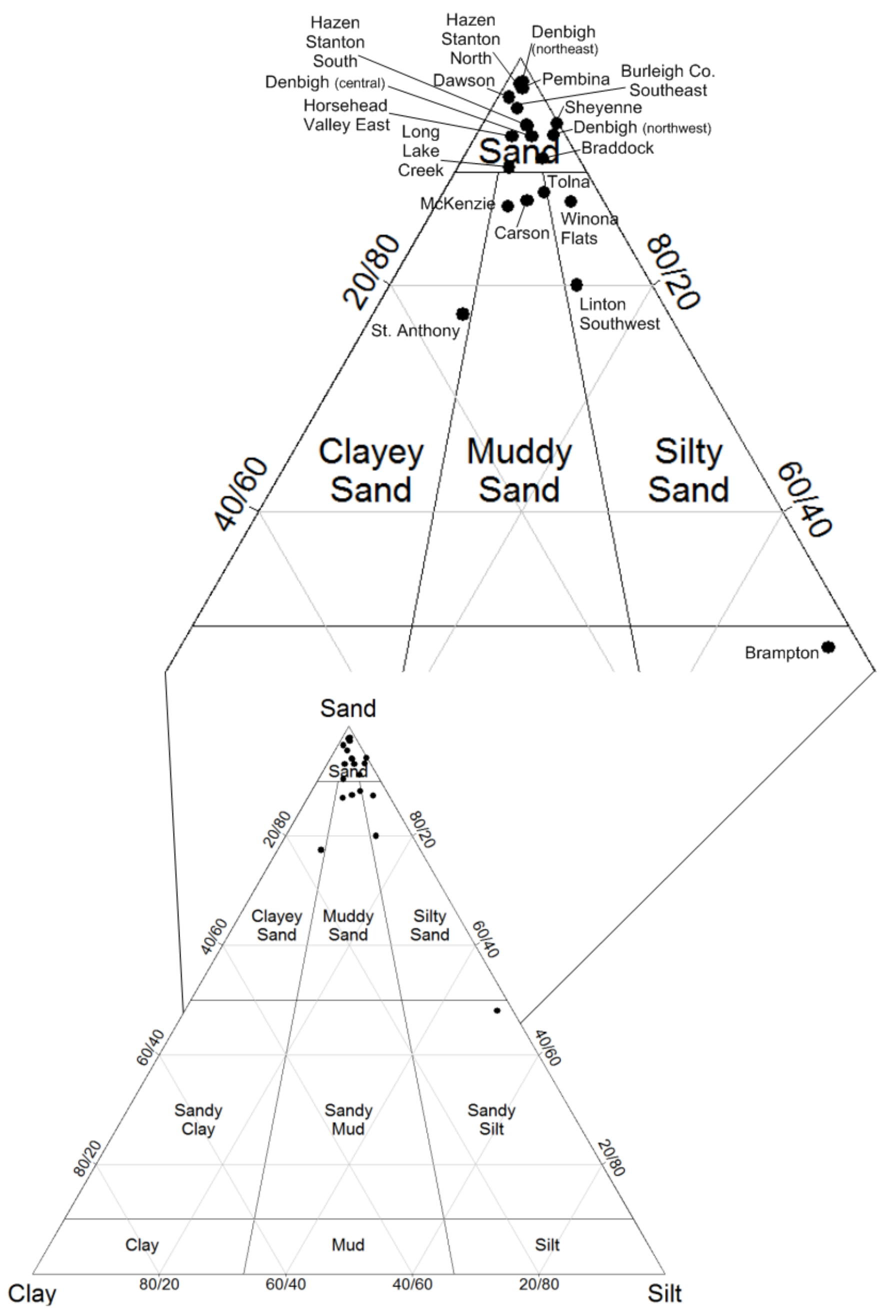

Figure A-II-1. Ternary diagram (axes in percent) of eolian sand textural classifications (after Folk, 1954) based on gradational analysis of twenty selected dune deposits in North Dakota.

GRAIN SIZE DISTRIBUTION

NORTH DAKOTA DEPARTMENT OF TRANSPORATION
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PROJECT NUMBER NDGS Eolian Sand Gradations **LOCATION** County

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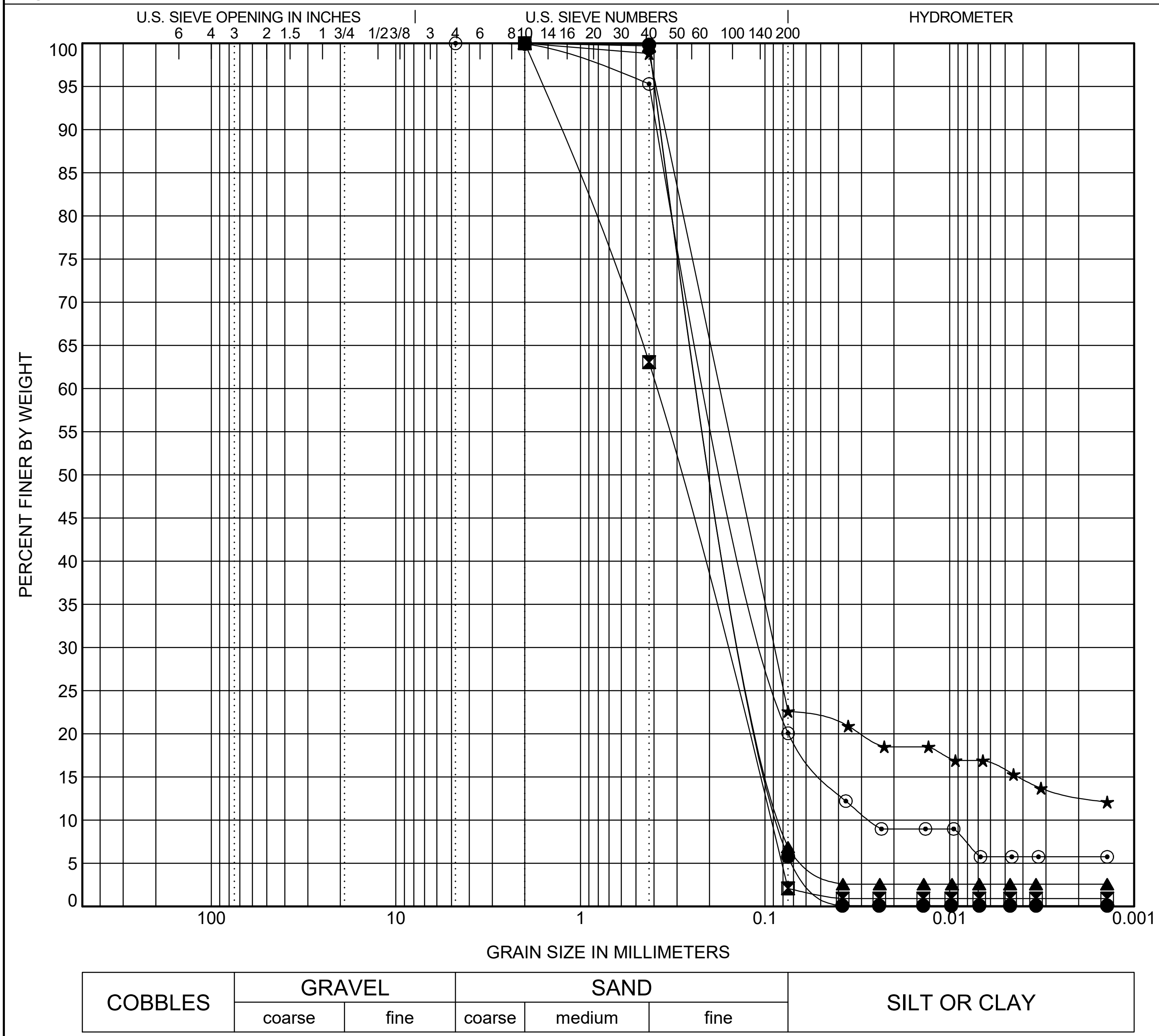

SAMPLE	3/8"	#4	#10	#40	#200	2	5	15	30	60	130	250	1440
● **Sheyenne Dunes**	**100**		**100.0**	**99.8**	**5.8**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
⊠ **Denbigh Dunes (northeast)**	**100**		**100.0**	**63.1**	**2.1**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
▲ **Denbigh Dunes (central)**	**100**		**100.0**	**99.7**	**6.9**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**
★ **St. Anthony Dunes**	**100**		**100.0**	**98.8**	**22.6**	**21.0**	**18.8**	**18.5**	**17.1**	**16.9**	**15.5**	**14.0**	**12.1**
⊙ **Linton Southwest Dunes**	**100**	**100.0**	**99.9**	**95.3**	**20.1**	**12.2**	**9.2**	**9.0**	**9.0**	**5.9**	**5.7**	**5.7**	**5.7**

SAMPLE	D100	D60	D30	D10	%Gravel	%Sand	%Silt	%Clay
● **Sheyenne Dunes**	**0.0365**	**0.204**	**0.117**	**0.081**	**0.0**	**94.2**	**5.7**	**0.1**
⊠ **Denbigh Dunes (northeast)**	**0.0365**	**0.39**	**0.166**	**0.094**	**0.0**	**97.9**	**1.2**	**0.9**
▲ **Denbigh Dunes (central)**	**0.0365**	**0.202**	**0.116**	**0.08**	**0.0**	**93.1**	**4.3**	**2.6**
★ **St. Anthony Dunes**	**0.0365**	**0.176**	**0.089**		**0.0**	**77.4**	**6.9**	**15.7**
⊙ **Linton Southwest Dunes**	**0.0365**	**0.188**	**0.094**	**0.027**	**0.0**	**79.9**	**14.3**	**5.7**

GRAIN SIZE DISTRIBUTION

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PROJECT NUMBER NDGS Eolian Sand Gradations **LOCATION** County

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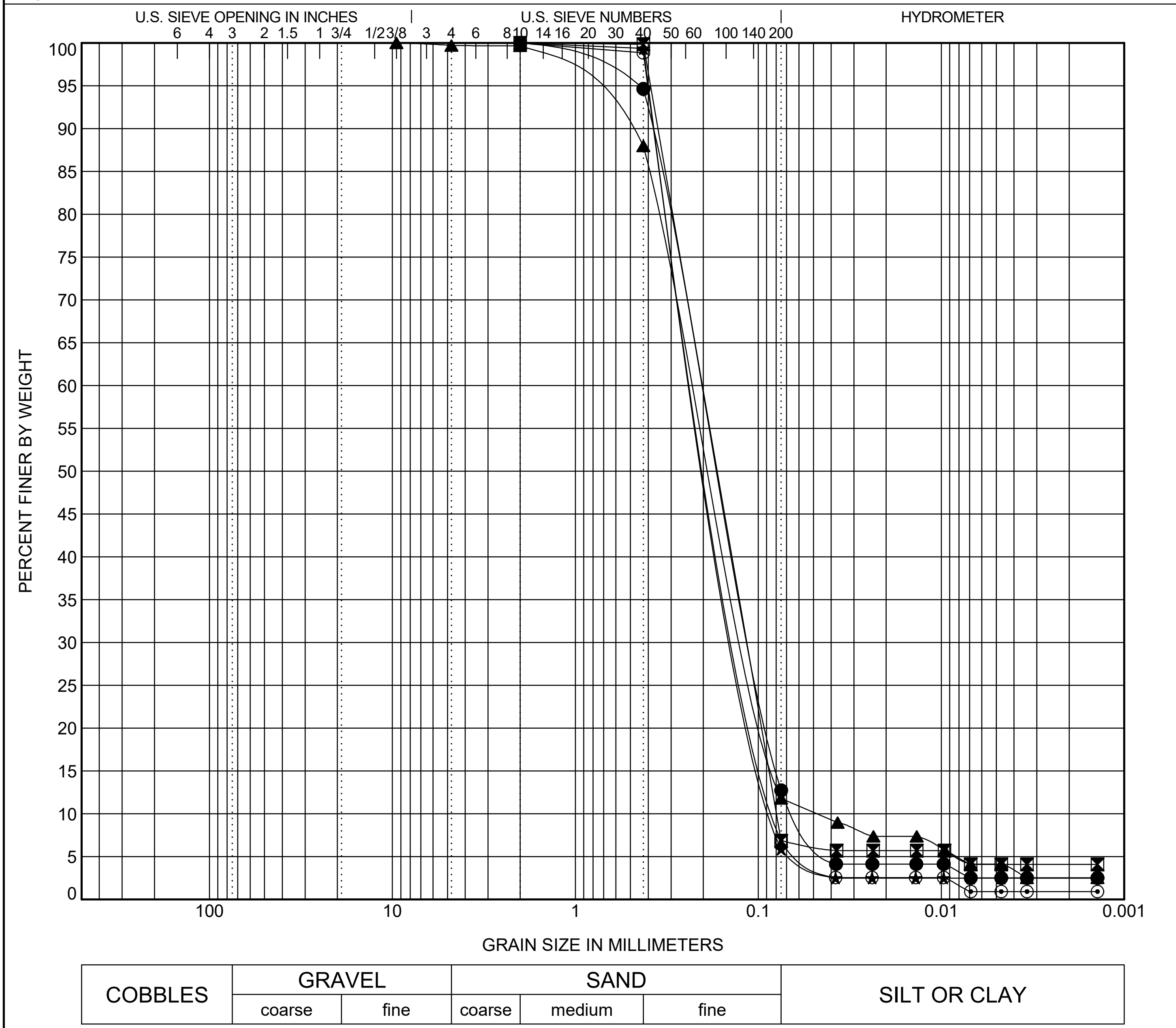

SAMPLE	3/8"	#4	#10	#40	#200	2	5	15	30	60	130	250	1440
● **Winona Flats Dunes**	**100**		**100.0**	**94.6**	**12.7**	**4.2**	**4.1**	**4.1**	**4.1**	**2.5**	**2.5**	**2.5**	**2.5**
⧗ **Horsehead Valley East**	**100**		**100.0**	**99.8**	**6.9**	**5.7**	**5.7**	**5.7**	**5.7**	**4.1**	**4.1**	**4.1**	**4.1**
▲ **Tolna Dunes**	**100**	**99.7**	**99.7**	**88.0**	**11.8**	**9.1**	**7.4**	**7.4**	**5.8**	**4.1**	**4.1**	**2.5**	**2.5**
★ **Hazen-Stanton (south)**	**100**		**100.0**	**99.4**	**5.9**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
⊙ **Denbigh Dunes (northwest)**	**100**		**100.0**	**98.8**	**6.8**	**2.6**	**2.6**	**2.6**	**2.6**	**0.9**	**0.9**	**0.9**	**0.9**

SAMPLE	D100	D60	D30	D10	%Gravel	%Sand	%Silt	%Clay
● **Winona Flats Dunes**	**0.0378**	**0.204**	**0.108**	**0.06**	**0.0**	**87.3**	**10.2**	**2.5**
⧗ **Horsehead Valley East**	**0.0378**	**0.202**	**0.115**	**0.08**	**0.0**	**93.1**	**2.8**	**4.1**
▲ **Tolna Dunes**	**0.0378**	**0.225**	**0.114**	**0.048**	**0.3**	**87.9**	**7.7**	**4.1**
★ **Hazen-Stanton (south)**	**0.0378**	**0.205**	**0.117**	**0.081**	**0.0**	**94.1**	**3.4**	**2.5**
⊙ **Denbigh Dunes (northwest)**	**0.0378**	**0.204**	**0.116**	**0.08**	**0.0**	**93.2**	**5.9**	**0.9**

GRAIN SIZE DISTRIBUTION

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PROJECT NUMBER NDGS Eolian Sand Gradations **LOCATION** County

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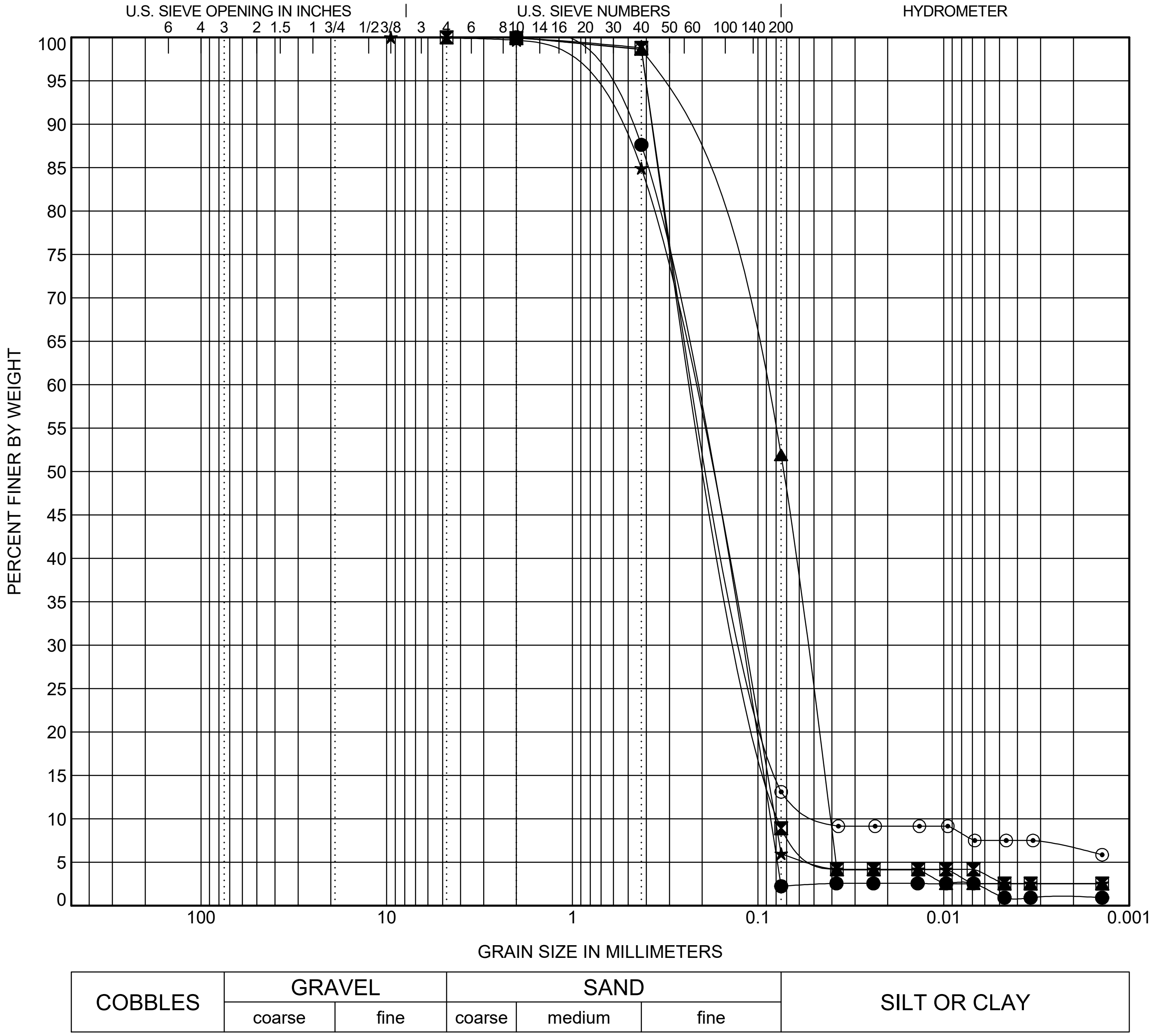


SAMPLE	3/8"	#4	#10	#40	#200	2	5	15	30	60	130	250	1440
● **Hazen-Stanton (north)**	**100**		**100.0**	**87.6**	**2.2**	**2.6**	**2.6**	**2.6**	**2.6**	**2.6**	**0.9**	**0.9**	**0.9**
⊠ **Braddock Dunes**	**100**	**100.0**	**99.9**	**98.8**	**8.9**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**	**2.5**	**2.5**	**2.5**
▲ **Brampton Dunes**	**100**		**100.0**	**98.6**	**51.9**	**4.1**	**4.1**	**4.1**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
★ **Tappen Dunes**	**100**	**99.9**	**99.7**	**84.9**	**6.0**	**4.2**	**4.2**	**4.2**	**4.2**	**2.5**	**2.5**	**2.5**	**2.5**
⊙ **McKenzie Dunes**	**100**		**100.0**	**98.6**	**13.1**	**9.1**	**9.1**	**9.1**	**9.1**	**7.6**	**7.5**	**7.5**	**5.9**

SAMPLE	D100	D60	D30	D10	%Gravel	%Sand	%Silt	%Clay
● **Hazen-Stanton (north)**	**0.0369**	**0.194**	**0.083**	**0.047**	**0.0**	**97.8**	**1.1**	**1.2**
⊠ **Braddock Dunes**	**0.0369**	**0.201**	**0.113**	**0.077**	**0.0**	**91.1**	**6.1**	**2.8**
▲ **Brampton Dunes**	**0.0369**	**0.101**	**0.055**	**0.041**	**0.0**	**48.1**	**49.4**	**2.5**
★ **Tappen Dunes**	**0.0369**	**0.246**	**0.127**	**0.082**	**0.1**	**93.9**	**3.5**	**2.5**
⊙ **McKenzie Dunes**	**0.0369**	**0.194**	**0.106**	**0.043**	**0.0**	**86.9**	**5.6**	**7.5**

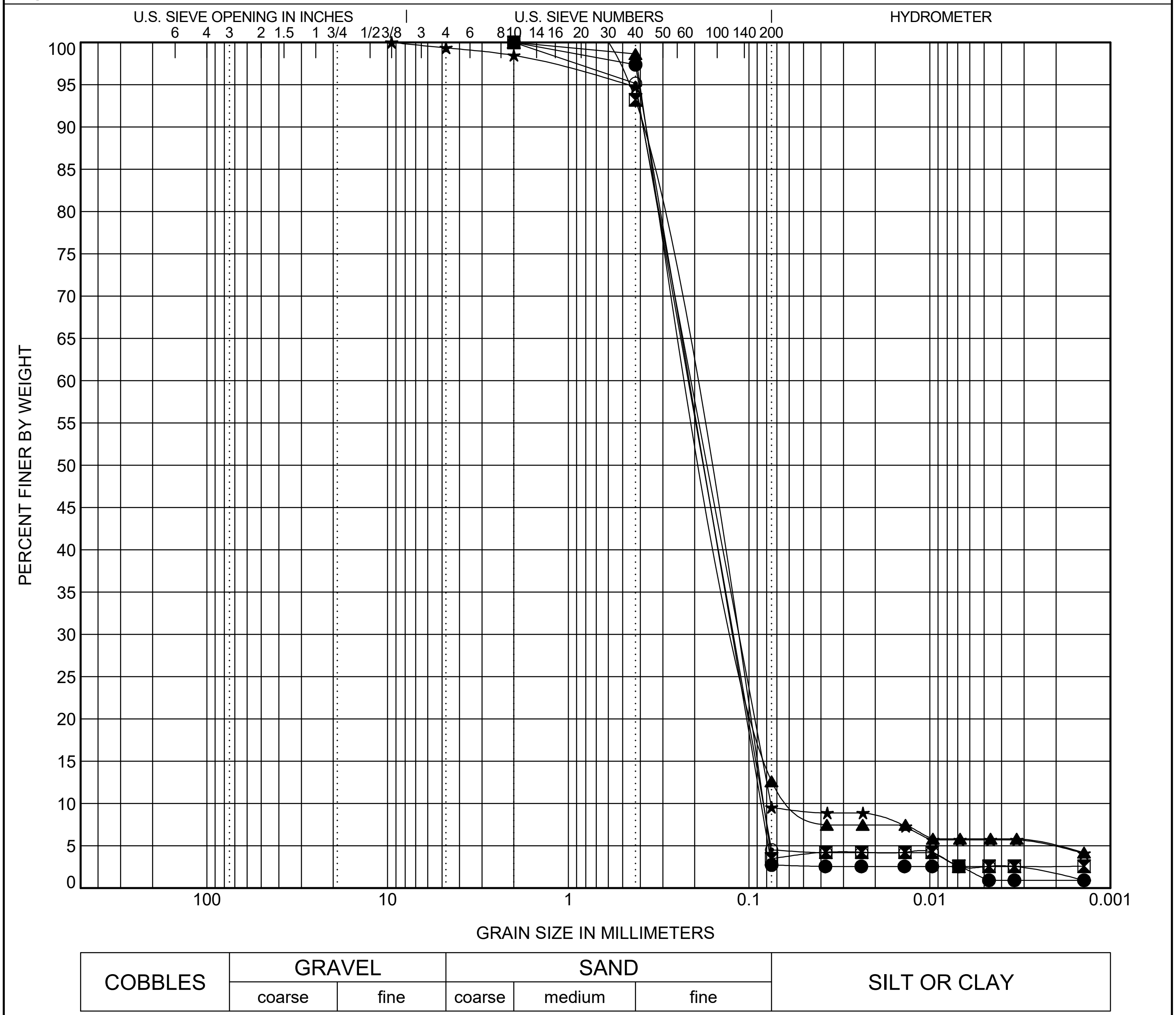
NDGS GRAIN SIZE DISTRIBUTION - NDDOT_DATATEMP_20180208.GDT - 5/22/18 10:43 - F:\LAB\PROJECTS\GINT\NDGS FRAC SAND.GPJ

GRAIN SIZE DISTRIBUTION

NORTH DAKOTA DEPARTMENT OF TRANSPORATION
300 AIRPORT ROAD
BISMARCK, ND 58504

PROJECT NUMBER NDGS Eolian Sand Gradations **LOCATION** County

Page 4-4



SAMPLE	3/8"	#4	#10	#40	#200	2	5	15	30	60	130	250	1440
● Pembina Dunes	100		100.0	97.4	2.7	2.6	2.6	2.6	2.6	2.6	0.9	0.9	0.9
⧗ Dawson Dunes	100		100.0	93.2	3.5	4.2	4.2	4.2	4.2	2.6	2.6	2.6	2.6
▲ Carson Dunes	100		100.0	98.6	12.6	7.6	7.5	7.5	5.9	5.8	5.8	5.8	4.2
★ Long Lake Creek Dunes	100	99.4	98.5	94.7	9.5	8.9	8.9	7.3	5.7	5.7	5.7	5.7	4.1
⊙ Burleigh Co. Southeast	100		100.0	95.2	4.5	4.2	4.2	4.2	4.2	2.5	2.5	2.5	0.9

SAMPLE	D100	D60	D30	D10	%Gravel	%Sand	%Silt	%Clay
● Pembina Dunes	0.0376	0.214	0.124	0.086	0.0	97.3	1.5	1.2
⧗ Dawson Dunes	0.0376	0.172	0.076	0.044	0.0	96.5	0.9	2.6
▲ Carson Dunes	0.0376	0.195	0.106	0.052	0.0	87.4	6.8	5.8
★ Long Lake Creek Dunes	0.0376	0.21	0.114	0.076	0.6	89.8	3.9	5.7
⊙ Burleigh Co. Southeast	0.0376	0.217	0.122	0.083	0.0	95.5	2.0	2.5

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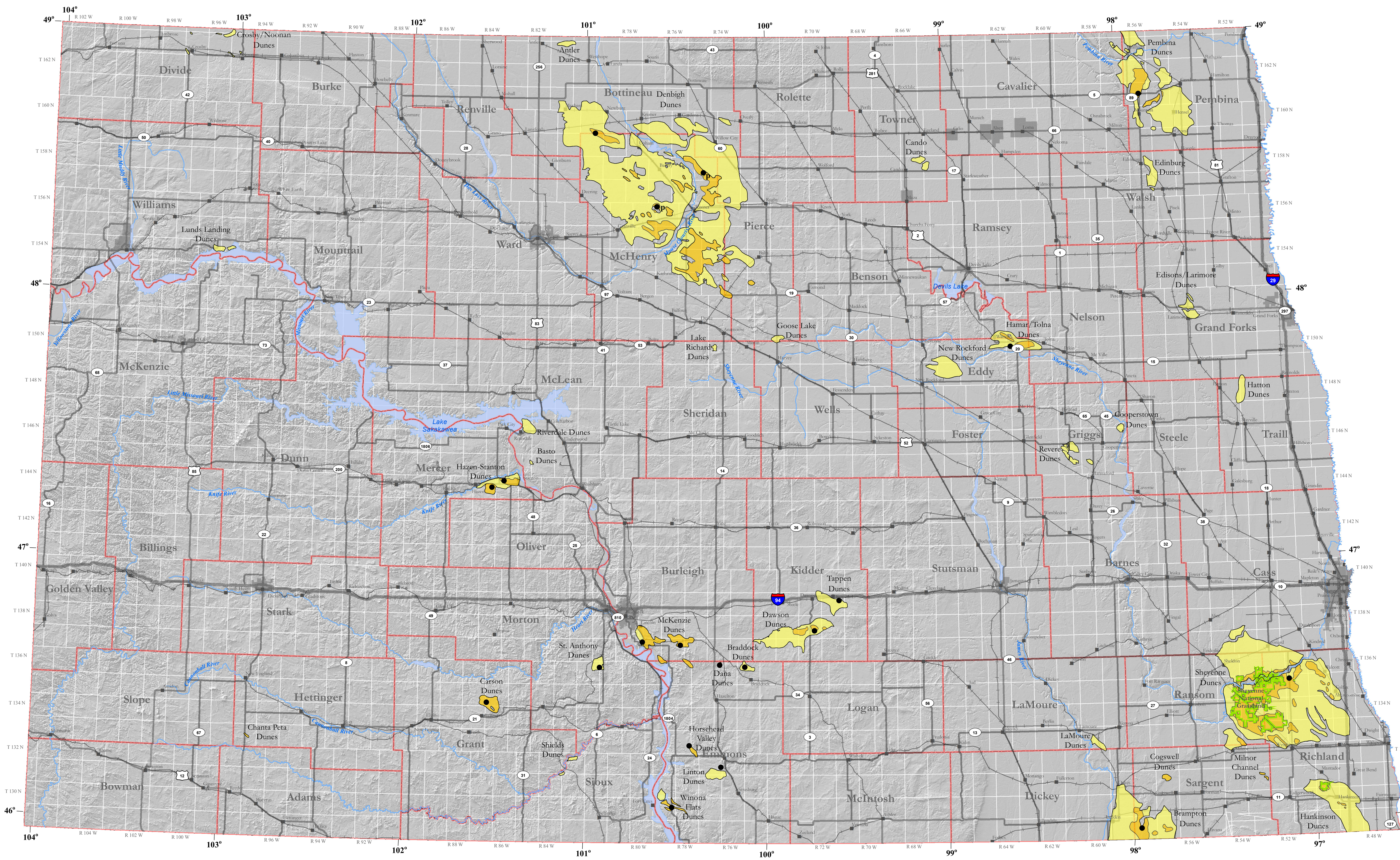
North Dakota Geological Survey
Geologic Investigations No. 207 - Plate I

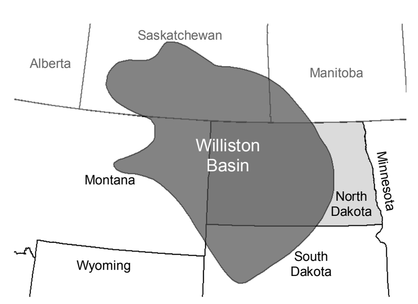
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources

Eolian Sands in North Dakota Evaluated for Proppant Use

Fred J. Anderson

2018





Scale 1:1,000,000

Miles: 0 10 20 30 40

Kilometers: 0 10 20 30 40

North American Datum 1983 Lambert Conformal Conic

North Dakota Geological Survey
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DISCUSSION

This map presents the 36 areas of the state where eolian (i.e. wind-blown) sand deposits in the form of low relief dunes and sheet sands (Qtou) and high-relief (Qod) dunes are found. The largest deposits of dune sands, greater than 500 square miles (320,000 acres) in areal extent (Table 1), are found in the north-central part of the state in McHenry County; the Denbigh Dunes, which originated from the glaciofluvial and glaciolacustrine sediments of the former Glacial Lake Souris, and the southeastern corner of the state in eastern Ransom and northern Richland counties; the Sheyenne Dunes, that developed on the sediments of the Sheyenne Delta of the former Glacial Lake Agassiz. Both of these dune areas have portions of their deposits within protected areas such as the Sheyenne National Grasslands and the Denbigh Experimental Forest. Several of the smaller dune areas are also coincident with state or federal Wildlife Management Areas. The eolian sand deposits in North Dakota are young, late Pleistocene to Holocene in age, and as a result are texturally (i.e. less well rounded and sorted) and compositionally immature (i.e. variable mineralogy as opposed to pure quartz sand) and may be characterized as only two-cycle depositional sediments. Sand transport directions have been dominantly from the northwest to the southeast consistent with the dominant paleoclimatic wind regimes. The locations where dune sand samples have been collected for materials testing and sedimentological analysis in support of sand source characterization for use as natural proppant sand for oil and gas wells are also shown. The intent of this map is as an exploratory tool in the continued exploration and characterization of North Dakota's surficial sand resources for potential use as proppant and other industrial sand uses.

EXPLANATION

Eolian Sand Deposits

Qod **Eolian Sand in High-Relief Dunes**

Windblown sand; well sorted, fine grained up to 30 feet (10 meters) thick or greater, occurring in localized dune deposits.

Qtou **Eolian Sand in Low-Relief Dunes**

Windblown sand; up to 10 feet (3 meters) in thickness, commonly found bounding areas of localized high-relief sand dunes as low-relief dune fields or rolling sheet sands.

Locations of Recent Sampling Sites

● Locations where reconnaissance-level field sampling was completed during the 2009 and 2010 field seasons. These locations were identified as candidates for materials testing and sedimentological characterization for use as proppant sands.

●p Eolian sand sample location tested for proppant suitability.

Misc

Water

River/Creek

Cities/Towns

National Grassland

County Boundaries

Highways

Railroad

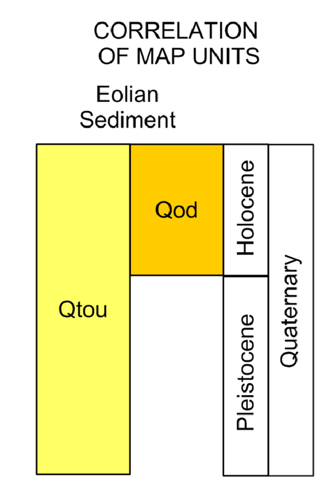

Table 1: Areal extent of eolian sand areas in North Dakota

Dune Area Name	County	Area (mi^2)	Acres
Denbigh Dunes	McHenry/Pierce/Bottineau	989.57	632,913.80
Sheyenne Dunes	Cass/Ransom/Sargent/Richland	687.15	439,525.39
Pembina Dunes	Cavalier/Pembina	208.19	133,107.24
Brampton Dunes	Dickey/Sargent	152.36	97,390.36
Hankinson Dunes	Richland	110.00	70,351.61
Dawson Dunes	Kidder	72.58	46,417.13
McKenzie Dunes	Burleigh/Emmons	39.93	25,539.10
Hamar/Tolna Dunes	Benson/Eddy/Nelson	39.56	25,301.03
New Rockford Dunes	Eddy	33.73	21,574.06
Hazen-Stanton Dunes	Mercer	28.86	18,473.26
Tappen Dunes	Kidder	21.17	13,537.99
Edinburg Dunes	Walsh	16.25	10,393.45
Carson Dunes	Grant	15.70	10,049.41
Revere Dunes	Griggs	13.93	8,907.07
Edisons/Larimore Dunes	Grand Forks	13.19	8,439.45
Hatton Dunes	Grand Forks/Traill	12.82	8,203.69
Linton Dunes	Emmons	11.54	7,375.53
Winona Flats Dunes	Emmons	11.00	7,035.30
Riverdale Dunes	McLean	9.97	6,381.54
St. Anthony Dunes	Morton	8.84	5,653.52
Cando Dunes	Towner	7.76	4,961.65
LaMoure Dunes	LaMoure/Dickey	6.65	4,251.79
Braddock Dunes	Burleigh/Emmons	5.76	3,682.26
Lunds Landing Dunes	Williams	5.41	3,469.81
Antler Dunes	Bottineau	5.15	3,294.91
Crosby/Noonan Dunes	Divide	5.01	3,209.50
Goose Lake Dunes	Pierce/Wells	4.37	2,793.68
Cooperstown Dunes	Griggs	3.17	2,026.60
Horsehead Valley Dunes	Emmons	3.03	1,939.38
Cogswell Dunes	Sargent	2.87	1,836.83
Shields Dunes	Sioux	2.82	1,801.16
Lake Richard Dunes	Sheridan	1.59	1,018.62
Milnor Channel Dunes	Sargent	1.33	852.60
Dana Dunes	Emmons	0.74	474.84
Chanta Peta Dunes	Hettinger	0.66	419.75
Basto Dunes	McLean	0.65	419.12
	Total All Dunes Areas	**2,553.35**	**1,633,022.44**

SELECTED MAP REFERENCES

Anderson, F.J., 2011, Investigation of Sand Resources in North Dakota: Sedimentological Characterization of Surficial Sand Deposits for Potential Use as Proppant, North Dakota Geological Survey, Report of Investigation No. 110, 67 pp.

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Cartographic Compilation: Navin Thapa