Evaluation of Windblown Sand Deposits in South-Central North Dakota for Potential Use as Proppant

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Abstract

Sampling and testing of windblown sand deposits in south-central North Dakota was completed in 2020 in order to characterize these deposits for potential use as proppant in the hydraulic fracturing of oil and gas wells in the Williston Basin. Proppant sand testing was performed on 14 samples from 11 individual windblown sand areas in southern Burleigh, southern Kidder, and northern and southwestern Emmons Counties. These windblown sand deposits are found in localized low-relief (<10-ft) and high-relief (>10-ft) dune settings and cover approximately 167 square miles. Selected sand size classes (typically 40/70 and 70/140) were tested as these represented the most abundant grain sizes which are consistently well sorted, medium to very-fine grained, and contain crush resistance ranging from 4,000 to 5,000 psi (4K to 5K). Acid solubility averaged 7.7% and turbidity 73% with very low loss on ignition (LOI) values averaging 0.6%, suggesting a low presence of detrital lignite and deleterious mineralogy. Sand grain particle shape factors approach the desired ranges for proppant use and average 0.5 for roundness and 0.8 for sphericity. Mineralogically, no carbonates were found in the washed and sized samples which averaged 68% quartz, 30% feldspars (albite and microcline), and 2.7% clays (illite) with minor amounts of chlorite (chamosite). Some of these windblown sand deposits may be suitable for use as proppant given current industry requirements but are of lower quality when compared to the windblown sand deposits found in the Hazen-Stanton and Denbigh Dunes where proppant sand is currently being mined.

Acknowledgements

The author would like to thank the various private landowners who provided access to many of the sampling areas contained in this report along with the North Dakota Department of Trust Lands for access to many of the dune fields located on Trust Lands. Sand testing services (proppant analysis) were provided by Lonquist Frac Sand Services in College Station, Texas. Cartographic support was provided by Mr. Navin Thapa, GIS Specialist with the North Dakota Geological Survey. Bulk sand photomicrography was completed by Mr. Levi Moxness, Geologist with the NDGS. Additional review and comments were provided by Mr. Levi Moxness and Mr. Ed Murphy.

Author's Note

Recently the oil and gas industry has relaxed proppant testing specifications in parts of the U.S. in favor of more regional or local proppant sand source utilization. In-basin proppant sand is currently being produced from the Hazen-Stanton Dunes in Mercer County and Denbigh Dunes in McHenry County. This report characterizes the windblown sands that are found in south-central North Dakota, expanding the view of the possibilities for continued development of proppant sand resources across the state.

Cover photo: A high-relief dune in the central Lincoln Dunes southeast of Lincoln, North Dakota. Dunes like this are common in this area in southwestern Burleigh County and can reach heights of up to 30 feet.

TABLE OF CONTENTS

TABLE OF CONTENTS *(Contd.)*

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

APPENDICES

LIST OF APPENDIX FIGURES

TABLE OF CONTENTS *(Contd.)*

LIST OF APPENDIX TABLES

INTRODUCTION

A renewed interest in the possibility of locating in-basin proppant sand resources in North Dakota started in 2018 as falling oil prices forced companies to take a closer look at all aspects of the development equation. Local proppant sand sourcing was identified as an area for potential savings in the Williston Basin, as was currently being realized in other shale basins in the U.S., e.g., the Permian Basin in Texas. As a result, the Survey embarked on renewed exploration for potential proppant sand deposits that were closer to the heart of oil development activity in west-central North Dakota.

Windblown sand deposits were identified early in the exploration process as possible candidates for proppant sand use. The natural processes that produce windblown deposits preferentially transport and deposit sand in a generally uniform depositional setting (i.e. dunes) and thus became the operating depositional model for continued proppant sand resource evaluation and testing. Sampling and testing efforts were recently concentrated in the Hazen-Stanton and Denbigh Dunes because they are the largest expanses of windblown sand in North Dakota that happen to be closest to the heart of current oil development activity in the Williston Basin.

There are also multiple windblown sand deposits across south-central and eastern North Dakota that although they are of greater distances from the current use areas, that may also be suitable for proppant sand use. Fourteen sand samples from eleven windblown sand deposits were collected during the 2019 and 2020 field seasons and submitted to Lonquist Field Services in College Station, Texas, for proppant testing and characterization. Bulk sand samples were collected in five-gallon buckets at 13 locations (Samples No. 1 – 14, this report) distributed across southern Burleigh\Kidder Counties and in northern and western Emmons County (Figure 1). Samples were collected from within areas of low-relief (<10 feet) sand dunes as well as high-relief (>10 feet) dunes in larger dune fields (Table 1). Samples were collected from within the dunes beneath the vegetative cover and weathered surface horizons (generally two to three feet below land surface) using traditional hand excavation tools such as a pick and shovel, as in Anderson (2011).

Sand samples were evaluated for proppant suitability in accordance with testing standards and specifications published by the American Petroleum Institute (API): API STD-19C (API, 2018) and the International Organization for Standardization (ISO): ISO 13503-2 (ISO, 2006). Testing included: gross sample inspection and field description (including field acid reactivity), sample washing and comparison, stereo microscope photomicrography, particle shape factors (i.e. roundness and sphericity) analysis, qualitative and quantitative mineralogy via X-ray diffraction (XRD), crush resistance, acid solubility, turbidity, loss on ignition, and sand density testing. Tests were again performed on the most abundant size classes, as determined by sieve analysis, which typically fell into the 40/70 and 70/140 size classes.

Over the past decade, desired sand specifications have changed with continued refinements in the hydraulic fracturing process. Sand in the coarser size classes (e.g. 30/50) were originally preferred, which over time has changed to the finer sand size classes in the 40/70 and 70/140 ranges which generally demonstrate much higher crush resistance than coarser fractions.

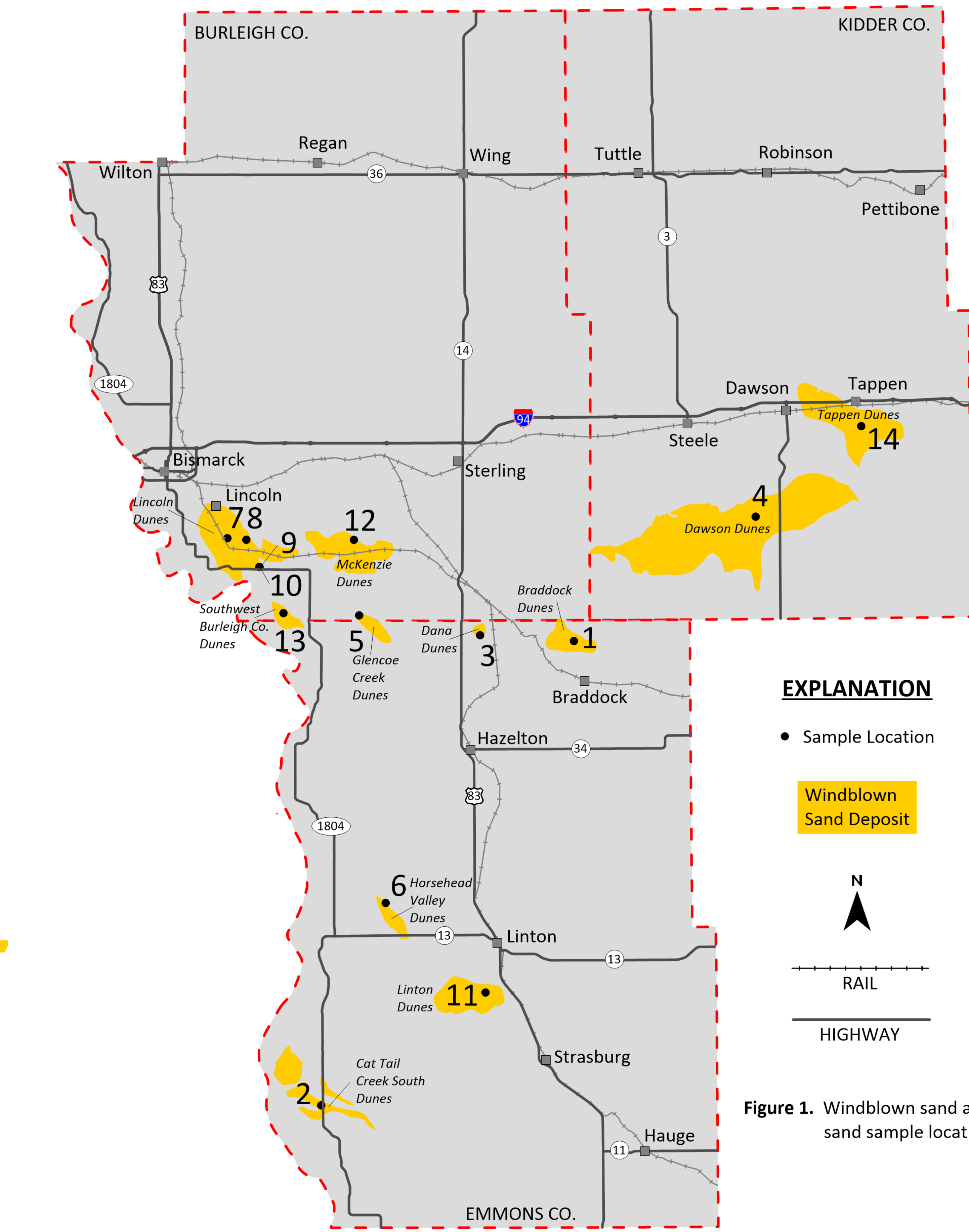

Figure 1. Windblown sand areas and sand sample locations.

Table 1. Sample Location Summary

Sample No.	Windblown Sand Area	County	Location (PLSS)	Description	Analytical Testing Completed		Field Acid Reactivity (10% HCl)
					Bulk Sand XRD Mineralogy	API 19C Proppant (wXRD)	
1	Braddock Dunes	Emmons	136-75-9-NW	Low Dunes, Ground Exposure	X	X	NR
2	Cat Tail Creek South Dunes	Emmons	130-79-14-NE	High Dunes, Dune Face Exposure	X	X	NR
3	Dana Dunes	Emmons	136-76-8-NW	High Dunes, Dune Face Exposure	X	X	NR
4	Dawson Dunes	Kidder	138-72-20-SW	Low Dunes, Ground Exposure	X	X	NR
5*	Glencoe Creek Dunes	Burleigh	137-78-36-SE	High Dunes, Dune Face Exposure	X	X	NR
6	Horsehead Valley Dunes	Emmons	133-78-24-SE	Low Dunes, Ground Exposure	X	X	NR
7	Lincoln Dunes (LD-1)	Burleigh	138-79-32-SE	High Dunes, Dune Face Exposure	X	X	NR
8	Lincoln Dunes (LD-2)	Burleigh	138-79-33-SE	Low Dunes, Ground Exposure	NT	X	NR
9	Lincoln Dunes (LD-3u)	Burleigh	137-79-11-SW	High Dunes, Dune Face Exposure	NT	X	NR
10	Lincoln Dunes (LD-4l)	Burleigh	137-79-11-SW	High Dunes, Dune Face Exposure	NT	X	NR
11*	Linton Dunes	Emmons	132-77-36-SE	Low Dunes, Ground Exposure	X	X	NR
12*	McKenzie Dunes	Burleigh	138-78-36-SW	High Dunes, Dune Face Exposure	X	X	NR
13*	Southwest Burleigh Dunes	Burleigh	137-79-36-NE	High Dunes, Dune Face Exposure	X	X	NR
14	Tappen Dunes	Kidder	139-71-14-NW	Low Dunes, Ground Exposure	X	X	NR

** = Sample locations on ND State Trust Lands.*

NR = Non-Reactive.

NT = Not Tested.

PREVIOUS WORKS

Earlier work on proppant sand suitability in North Dakota was completed by Anderson (2011) as North Dakota Geological Survey (Survey) Report of Investigation No. 110. Ten samples were tested and characterized from several different sources across the state, including: windblown, glacio-fluvial, and bedrock sandstone sources. In the end, it was concluded that North Dakota's sand deposits were approaching the desired specifications for proppant sand but fell short when compared to the higher quality Ottawa White sandstone deposits found in the Midwestern United States.

In 2018 the oil and gas industry expressed interest in sourcing their proppant sand from in-basin sources in order to avoid the high transportation costs associated with importing sands from other parts of the U.S., particularly the upper-Midwest, and from overseas. Windblown sand deposits (along with bedrock sandstones in western North Dakota) were selected for renewed study because they contain little overburden and have relatively consistent sedimentologic characteristics such as uniformity of grain size and mineralogy. As a first step in this renewed project, the Survey published Geologic Investigation No. 207 (Anderson, 2018) a compilation of the available geologic information on windblown sand deposits across the state, including grain size and general composition.

Based on continued feedback from industry about the importance of sourcing sand from deposits near the heart of oil and gas activity in the Bakken, the study focused on fully characterizing the eolian sand deposits near Hazen and Stanton in west-central North Dakota, the largest deposit closest to the heart of oil activity (Anderson, 2019a). The Hazen-Stanton investigation consisted of sampling the high-relief dune fields. It was concluded that the sand deposits in this area may be suitable for use as proppant sand.

In early 2019, attention turned to initial testing of eolian sand deposits in north and south-central North Dakota and consisted of reconnaissance style (i.e. limited sampling) investigation of eolian sand found near Carson in Grant County, Lincoln in southwestern Burleigh County, the Lake Richard Dunes in northern Sheridan County, and the southernmost Denbigh sands south of Towner (Anderson, 2019b).

Continued interest by industry in sand deposits in the Denbigh area prompted the further evaluation of the extensive, although somewhat localized dune deposits, found throughout North Central North Dakota and dominantly within McHenry County in 2019. Extensive proppant sand testing and characterization work was performed across the Denbigh Windblown Sands area (Anderson, 2020a) which concluded that deposits in these areas are and would continue to be suitable as in-basin sources of natural sand proppant. Additional mineralogical study of unprocessed in-situ "bulk" sand was also completed on these same deposits in McHenry County in order to provide a more comprehensive understanding of in-place dune deposit characteristics (Anderson, 2020b).

In 2020 the Survey continued sampling and testing work on dune deposits in south-central North Dakota in southern Burleigh and Kidder, and northern and western Emmons Counties, the results of which are included in this report. Future investigation of windblown deposits found scattered across eastern North Dakota and the northern and southern Red River Valley are planned.

WINDBLOWN SAND IN SOUTH-CENTRAL NORTH DAKOTA

Areas of windblown sand in south-central North Dakota are found in southern Burleigh and Kidder counties and northern and western Emmons County (Clayton, et al, 1980). These deposits are more localized as compared to some of the other larger expanses of windblown sand in the state such as the Denbigh Dunes, which stretch across the northern two-thirds of McKenzie and surrounding counties in north-central North Dakota, or the Pembina and Sheyenne Dunes located in the northern and southern Red River Valley.

There are eleven previously mapped windblown sand areas containing dunes of low-relief and undulating tabular sheet sands generally less than 10-ft in height (<3m) and smaller areas within these that contain coalesced high-relief dunes generally greater than 10-ft (3m) in height but in some locations can reach heights of up to 30 feet (10m) or more (Table 1). These sand deposits originate from local glacial outwash plains, regional proglacial lacustrine deposits, and ancient and modern floodplains. All the windblown sands in these areas tend to be under vegetative cover (crop lands, grasses, shrubs, and trees) with only the occasional blowout, dune face, or ground exposure revealing the character of the underlying sand. Collectively these areas cover approximately 167.5 square miles (433.8 km^2) or 107,224 acres.

High-Relief Dunes

There are eight windblown sand areas that contain high-relief dunes and include (from largest to smallest): the Lincoln, McKenzie, Dawson, Cat Tail Creek, Horsehead Valley, Glencoe Creek, Burleigh Co. Southwest, and Dana dunes. These areas cover an estimated 123 square miles (319 km^2) or 78,664 acres. The high-relief dune fields tend to display a somewhat elongated trend from the northwest to the southeast (Plate I), in line with prominent paleo-wind directions. Eleven of the 14 samples collected as a part of this investigation, were from high-relief dune settings (Table 1).

Low-Relief Dunes

The other three windblown sand areas: the Tappen, Linton, and Braddock dunes contain gently rolling to flat tabular sheet sands with occasional low-relief dunes. These areas with low-relief dunes cover approximately 38 square miles (98 km^2) or 24,615 acres. Two of the 14 samples collected for this investigation were collected from areas with low-relief dunes (Table I). Some additional windblown sand of limited extent (not included in this investigation) mantling terrace deposits has been mapped in the Winona Flats area along the eastern edge of the Missouri River trench, north of Cat Tail Bay. There has been sand and gravel production from this area historically.

Dunes on Trust Lands

There is a total of nine tracts of Trust Lands within areas of windblown sand in south-central North Dakota that cover 3.2 square miles (8.2 km^2) or 2,028 acres. Only four locations on Trust Lands were sampled as a part of this investigation as these happened to be generally coincidental favorable sampling locations (Plate I).

SAND SAMPLE LOCATIONS

Bulk samples of windblown sand were collected in five-gallon buckets from selected deposits in southern Burleigh and Kidder Counties and northern and western Emmons County in 2019 and 2020. Each of the fourteen samples collected were submitted for proppant testing (Figure 1) by an independent material testing laboratory. None of the samples collected reacted to dilute (10%) HCL in the field suggesting sand devoid of carbonate or other potentially deleterious acid reactive minerals.

Sample No. 1 - Braddock Dunes

Sample No. 1 was collected from a hand-shovel pit excavated into a thin windblown deposit with undulating low-relief dunes mantling pre-existing glacial topography on the central portion of the Braddock Dunes in northeastern Emmons County in the NW 1/4 of Section 9, T. 136 N., R. 75 W. (Figure 2). This sample location is located approximately three miles northwest of Braddock.

Sample No. 2 – Cat Tail Creek South Dunes

Sample No. 2 was collected from a hand-shovel pit excavated into a northern facing high-relief dune exposure in the southern Cat Tail Creek South Dunes in southwestern Emmons County in the NE 1/4 of Section 14, T. 130 N., R. 79 W. (Figure 3). This sample location is located approximately 17 miles west of Strasburg and 9.5 miles north of the South Dakota border.

Sample No. 3 – Dana Dunes

Sample No. 3 was collected from a hand-shovel pit excavated into a southern facing high-relief dune exposure on the southern edge of the Dana Dunes in north-central Emmons County just south of the Emmons County line in the NW 1/4 of Section 8, T. 136 N., R. 76 W. (Figure 4). This sample location is located approximately four miles southwest of Moffit and 1.5 miles east of U.S. Highway 83.

Sample No. 4 – Dawson Dunes

Sample No. 4 was collected from a hand-shovel pit on a vegetated high-relief dune in the central portion of the Dawson Dunes in southern Kidder County in the SW 1/4 of Section 20, T. 138 N., R. 72 W. (Figure 5). This sample location is located approximately 10 miles southwest of Dawson and seven miles north of the Kidder/Logan County line.

Sample No. 5 – Glencoe Creek Dunes

Sample No. 5 was collected from a hand-shovel pit excavated into a southeastward facing high-relief dune exposure on the northwestern (presumably upwind) end of the Glencoe Creek Dunes in southern Burleigh County in the SE 1/4 of Section 36, T. 137 N., R. 78 W. (Figure 6). This sample location is one-half mile north of the Burleigh\Emmons County line and 14 miles southwest of Sterling on North Dakota Trust Lands.

Figure 2. View to the northwest across low-relief dunes located three miles northwest of Braddock in northeastern Emmons County (T.136N., R.75W., Sec.9, NW1/4). Sample No. 1 was collected from this location.

Figure 3. View to the northwest across high-relief dunes located 18 miles southwest of Strasburg in southwestern Emmons County (T.130N., R.79W., Sec.14, NE1/4). Sample No. 2 was collected from this location one mile south of Cat Tail Creek.

Figure 4. View to the north of south facing high-relief dune located four miles south of Moffit in northern Emmons County (T.136N., R.76W., Sec.8, NW1/4). Sample No. 3 was collected from this location.

Figure 5. View to the southeast along a low-relief dune located eight miles southwest of Dawson in southern Kidder County (T.138N., R.72W., Sec.20, SW1/4). Sample No. 4 was collected from this location.

Figure 6. View to the northwest of high-relief dunes located one-half mile north of the Burleigh-Emmons County line, 18 miles southwest of Bismarck in southern Burleigh County (T.137N., R.78W., Sec.36, SE1/4). Sample No. 5 was collected from this location.

Sample No. 6 – Horsehead Valley Dunes

Sample No. 6 was collected from a hand-shovel pit excavated into a low-relief south facing dune exposure along a road cut on the northwestern (presumably upwind) end of the Horsehead Valley Dunes in west-central Emmons County in the SE 1/4 of Section 24, T. 133 N., R. 78 W. (Figure 7). This sample location is located approximately ten miles west of Linton and four miles north of Beaver Creek.

Sample No. 7 – Lincoln Dunes (LD-1)

Sample No. 7 was collected from a hand-shovel pit excavated into a high-relief south facing dune exposure in the northern portion of the Lincoln Dunes in southwestern Burleigh County in the SE 1/4 of Section 32, T. 138 N., R. 79 W. (Figure 8). This sample location is located 2.3 miles southeast of Lincoln and one-half mile east of the Copper Ridge housing development.

Sample No. 8 – Lincoln Dunes (LD-2)

Sample No. 8 was collected from a hand-shovel pit excavated into a low-relief dune along a roadway exposure of the southeastern Lincoln Dunes in southwestern Burleigh County in the SE 1/4 of Section 33, T. 138 N., R. 79 W. (Figure 9). This sample location is located approximately 3.5 miles southeast of Lincoln and 1.75 miles north of N.D. Highway 1804.

Sample Nos. 9 & 10 Lincoln Dunes (LD-3u & LD-4l)

Sample Nos. 9 and 10 were collected from hand-shovel pits in a westward facing high-relief dune exposure at the southeastern (presumably downwind) end of the Lincoln Dunes in southwestern Burleigh County in the SW 1/4 of Section 11, T. 137 N., R. 79 W. (Figure 10). This sample location is located approximately 5.5 miles southeast of Lincoln and one-quarter mile north of N.D. Highway 1804. Sample LD-3u was collected from the upper portion of the dune which was separated by a weak paleosol horizon. Sample LD-4 was collected from the same dune in the lower portion of the dune.

Sample No. 11 – Linton Dunes

Sample No. 11 was collected from a hand-shovel pit in a ground exposure in a low-relief dune in the northeastern portion of the Linton Dunes in central Emmons County in the SE 1/4 of Section 36, T. 132 N., R. 77 W. (Figure 11). This sample location is located approximately 3.5 miles southwest of Linton (one mile southwest of the airport) on North Dakota Trust Lands.

Sample No. 12 – McKenzie Dunes

Sample No. 12 was collected from a hand-shovel pit excavated into a vegetation covered high-relief dune in the north-central portion of the McKenzie Dunes in southern Burleigh County in the SW 1/4 of Section 36, T. 138 N., R. 78 W. (Figure 12). This sample location is located approximately 7.3 miles southwest of McKenzie and 7.1 miles southeast of Menoken on North Dakota Trust Lands.

Figure 7. View to the southeast of low-relief dunes located ten miles west of Linton, in southwestern Emmons County (T.133N., R.78W., Sec.24, SE1/4). Sample No. 6 was collected from this location. This would be the northwestern end of the Horsehead Valley Dunes.

Figure 8. View to the northwest of high-relief dunes southeast of Lincoln, in southern Burleigh County (T.138N., R.79W., Sec.32, SE1/4). Sample No. 7 was collected from this location.

Figure 9. View to the north across the central portion of the Lincoln Dunes in southern Burleigh County (T.138N., R.79W., Sec.33, SE1/4). Sample No. 8 was collected from low-relief dunes along the northeastern margins of this dune field (NAIP, 2019).

Figure 10. View to the northwest of high-relief dunes southeast of Lincoln, in southern Burleigh County (T.137N., R.79W., Sec.11, SW1/4). Sample Nos. 9 & 10 were collected from this location in the upper and lower portions of the dune.

Figure 11. View to the northeast across low-relief dunes six miles southeast of Linton, in central Emmons County (T.132N., R.77W., Sec.36, SE1/4). Sample No. 11 was collected from this area on Trust Lands.

Figure 12. View to the north across high-relief dunes seven miles southwest of McKenzie, in southern Burleigh County (T.138N., R.78W., Sec.36, SW1/4). Sample No. 12 was collected at this location on Trust Lands. Winter sampling requires traditional pioneer tools such as pick and shovel in order to break through the frost layer.

Sample No. 13 – Southwest Burleigh Co. Dunes

Sample No. 13 was collected from a hand-shovel pit on a northwest facing exposure in a high-relief dune in the central portion of this vegetation covered dune field in southwestern Burleigh County in the NE 1/4 of Section 36, T. 137 N., R. 79 W. (Figure 13). This sample location is located two miles west of N.D. Highway 1804, one-half mile north of the Burleigh\Emmons County line, on North Dakota Trust Lands.

Sample No. 14 – Tappen Dunes

Sample No. 14 was collected from a hand-shovel pit along a vegetation covered high-relief dune in the southern portion of the Tappen Dunes in southeastern Kidder County in the SE 1/4 of Section 32, T. 138 N., R. 79 W. (Figure 14). This sample location is located approximately 1.5 miles south and east of Tappen.

Figure 13. View to the northwest across high-relief dunes next to the Missouri River floodplain 13 miles southeast of Bismarck, in southwestern Burleigh County (T.137N., R.79W., Sec.36, NE1/4). Sample No. 13 was collected at this location in the foreground on Trust Lands. The Missouri River Valley near Huff is visible in the left background.

Figure 14. View to the northwest across high-relief dunes two miles south of Tappen, in southeastern Kidder County (T.139N., R.71W., Sec.14, NW1/4). Sample No. 14 was collected from this location in the foreground along a vegetation-stabilized dune.

DESCRIPTION OF TESTING RESULTS

Windblown sand samples were tested in accordance with recommendations and specifications for proppant sand published by the American Petroleum Institute (API) and the International Organization for Standards (ISO). Testing included: particle size distribution (sieve analysis), analysis of grain morphology (sphericity and roundness), acid solubility, turbidity (amount of silt and clay fines), crush resistance, mineralogic evaluation, loss on ignition, and traditional material density testing. Long-term conductivity testing was not performed during this investigation due to budgetary considerations. Testing and analyses were completed by Lonquist Field Services, Inc., labs located in College Station, Texas during the summer of 2020.

Sample Preparation

All samples submitted for testing were prepared for analysis by washing on the #200 sieve, drying, and disassociation (Table 2). An initial gradational analysis was first performed on prepared samples to determine the dominant sand size fraction. Remaining tests were then performed on the dominant sand size fraction, in this case sands falling within either the 40/70 or 70/140 size classification (Table 3).

Particle Size Distribution – Textural (Sieve) Analysis

Sieve analyses were conducted in order to quantify the different sized sand grains within an individual sample. A series of stacked, wire-mesh sieves of standard sizes was used to sieve each sand sample. Amounts of sand either being retained by the screen on each successively smaller opening sized sieve (% retained) or passing through the screen (% passing) was recorded and reported as tabular data (Table 4) or in graphical form on a grain-size distribution diagram (Figure 15).

The resulting graph and grain-size curves depict the volume 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 terms), will have much of the sample volume within or near the same size classes (Table 5), resulting in a very steep curve on the grain size distribution diagram (Figure 15). All samples selected for testing were well sorted (poorly graded) sands falling into the medium to very-fine grained size classes (Appendix I).

There are several slightly different types of sediment classification schemes (most notably): Modified Wentworth, Unified Soil Classification System (USCS), and American Association of State Highway and Transportation Officials (AASHTO). Generally, these classifications vary in where they draw the boundaries between different types of sediment (e.g. sand and gravel). The Modified Wentworth system was used in this study.

All samples fall into the grain size ranges for classification as a “sand” according to the Modified Wentworth classification scheme (Figure 15) and can be further characterized as well sorted (poorly graded) to very well sorted, medium to very-fine grained sands. All the samples had most grains fall in the 40/70 or 70/140 or “100 mesh” sand size ranges (Table 5).

Statistical analyses can be performed on data generated in a grain-size distribution diagram and used to quantitatively compare individual samples for potential engineering applications. The mean grain-size

Table 2. Wash Loss on Bulk Sample

Sample No.	Windblown Sand Area	Wash Loss (%)	Over-Size Waste (%)	Fines Waste (%)	Sample Total	
					Waste	Product[1]
1	Braddock Dunes	28.90	2.2	5.2	36.2	63.7
2	Cat Tail Creek South Dunes	5.90	12.9	5.9	24.7	75.3
3	Dana Dunes	3.70	0.8	6.7	11.2	88.8
4	Dawson Dunes	2.90	13.6	2.5	19.1	80.9
5*	Glencoe Creek Dunes	14.50	0.8	17.4	32.7	67.3
6	Horsehead Valley Dunes	33.10	0.7	6.8	40.6	59.4
7	Lincoln Dunes (LD-1)	15.28	15.1	2.0	32.3	67.7
8	Lincoln Dunes (LD-2)	7.10	1.8	4.2	13.1	86.9
9	Lincoln Dunes (LD-3u)	5.90	1.2	3.9	10.9	89.1
10	Lincoln Dunes (LD-4l)	7.20	1.0	5.9	14.1	85.9
11*	Linton Dunes	17.60	2.8	16.2	36.6	63.4
12*	McKenzie Dunes	5.80	0.7	5	11.5	88.5
13*	Southwest Burleigh Dunes	5.10	6.6	3.7	15.5	84.5
14	Tappen Dunes	8.00	12.4	6.2	26.6	73.4

[1] *Product defined as 40/70 & 70/140 sand.*

Table 3. Proppant Testing Analytical Summary of Windblown Sands in South-Central North Dakota

Sample No.	Windblown Sand Area	Tested Size Class	Quartz Content[1] (%)	Crush Resistance (K-Value)	Acid Solubility (%)	Shape Factors		ISO Mean Particle Dia. (mm)	Median Particle Dia. (mm)	Turbidity (FTU)	Loss on Ignition (%)	Bulk Density (pcf)	Absolute Density (g/cm^3)
						Roundness	Sphericity						
1	Braddock Dunes	70/140	67.3	5K	7.4	0.5	0.8	0.215	0.185	21.7	0.50	84.7	1.63
2	Cat Tail Creek South Dunes	40/70	71.0	5K	8.1	0.6	0.8	0.279	0.246	61.2	0.71	88.3	1.66
3	Dana Dunes	70/140	66.8	5K	7.3	0.5	0.8	0.196	0.183	128.0	0.52	84.2	1.60
4	Dawson Dunes	40/70	72.2	5K	6.3	0.6	0.8	0.294	0.296	51.3	0.23	90.9	1.67
5	Glencoe Creek Dunes	70/140	65.9	4K	10.1	0.5	0.8	0.167	0.149	93.5	0.95	81.8	1.57
6	Horsehead Valley Dunes	70/140	64.0	4K	8.3	0.7	0.6	0.156	0.142	13.6	0.69	81.9	1.39
7	Lincoln Dunes (LD-1)	70/140	75.2	5K	7.6	0.4	0.8	0.299	0.252	147.0	0.71	85.8	1.47
8	Lincoln Dunes (LD-2)	70/140	65.0	4K	7.8	0.5	0.8	0.203	0.184	77.8	0.57	83.6	1.59
9	Lincoln Dunes (LD-3u)	70/140	66.2	5K	7.8	0.5	0.8	0.208	0.196	117.0	0.52	84.8	1.62
10	Lincoln Dunes (LD-4l)	70/140	69.7	5K	7.4	0.5	0.8	0.195	0.182	82.5	0.54	83.7	1.60
11	Linton Dunes	70/140	58.9	4K	8.8	0.5	0.8	0.178	0.148	61.5	0.48	82.3	1.57
12	McKenzie Dunes	70/140	68.1	5K	7.4	0.5	0.8	0.198	0.187	88.2	0.57	83.3	1.61
13	Southwest Burleigh Dunes	40/70	71.8	4K	8.4	0.6	0.8	0.249	0.217	58.0	0.71	86.6	1.65
14	Tappen Dunes	40/70	72.0	5K	5.5	0.6	0.8	0.281	0.236	24.6	0.29	89.1	1.67

[1] *Washed Sample*

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.

pcf = pounds per cubic foot.

Table 4. Sample Sieve Analysis Results Summary (Weight % Retained)

Sample No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14
US Sieve No.	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	16	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	30	0.9	2.3	0.0	3.7	0.1	1.0	3.7	0.2	0.1	0.1	1.0	0.1	1.8	4.3
	40	1.6	11.4	0.8	10.3	0.9	0.0	14.0	1.6	1.2	1.0	2.4	0.6	5.1	9.1
	45	2.3	10.3	1.7	9.3	1.3	0.1	9.8	2.4	2.2	1.6	2.0	1.4	6.0	7.9
	50	5.2	12.4	5.9	12.9	3.6	0.4	10.1	5.5	6.5	4.7	3.4	5.1	10.7	11.4
	60	10.7	12.6	11.3	16.0	7.0	1.8	13.0	10.8	13.0	10.0	5.5	11.6	14.8	13.4
	70	13.9	10.3	14.3	12.9	8.5	4.4	11.7	13.8	16.7	14.2	6.9	16.2	13.5	11.4
	80	17.5	10.4	17.9	11.7	12.0	10.9	12.2	18.1	20.6	19.5	10.6	19.7	14.4	11.4
	100	18.7	10.5	19.4	10.1	16.2	22.6	11.0	20.8	19.2	20.7	16.8	19.9	14.3	11.1
	120	13.7	8.1	13.9	6.7	17.3	29.2	8.2	14.9	11.0	14.4	18.2	13.5	10.0	8.1
	140	7.7	5.5	7.8	3.7	12.8	19.4	4.0	7.2	5.4	7.5	13.6	6.7	5.4	5.2
	170	4.2	3.5	4.3	1.7	8.9	7.1	1.4	3.0	2.7	3.8	10.1	3.3	2.6	3.5
	200	2.9	2.3	2.3	0.8	8.6	2.9	0.8	1.4	1.4	2.3	7.3	1.8	1.2	2.8
	Pan	0.2	0.5	0.3	0.1	2.8	0.2	0.1	0.1	0.1	0.2	2.2	0.3	0.1	0.5
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 5. Percent Sand in Size Class Summary*

Sample No.	Sand in Size Class (%)			
	30/50	40/70	70/140	50/140
1	6.5	22.8	40.9	58.4
2	32.1	42.9	32.4	54.0
3	8.1	32.0	56.8	81.5
4	31.6	49.6	31.2	59.3
5	4.9	17.5	49.9	63.2
6	0.4	4.5	55.0	59.1
7	28.7	37.7	29.9	50.8
8	8.8	30.2	56.6	79.6
9	9.3	36.2	52.9	80.8
10	6.7	28.3	57.6	80.1
11	6.4	14.6	48.7	58.9
12	6.7	32.3	56.2	82.4
13	20.7	42.7	41.8	68.7
14	26.0	40.5	32.9	55.7

** Data derived from post wash-loss gradations.*

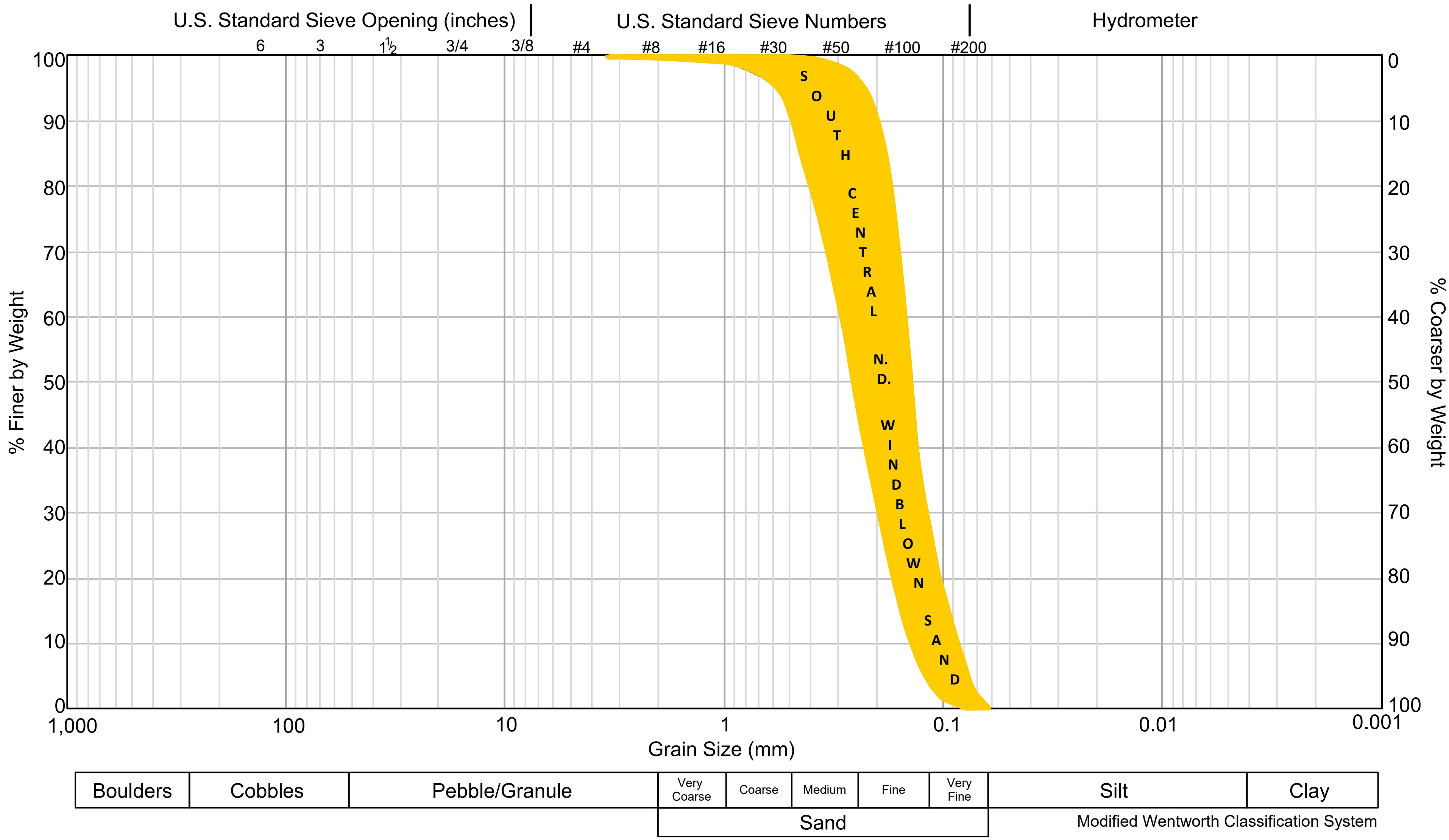

Figure 15. Range of 14 grain-size distribution curves (shaded-yellow) from windblown dune deposits in south-central North Dakota. These sands are well sorted and medium to very-fine grained according to the Modified Wentworth Classification System.

diameter is commonly used to characterize proppant distribution in hydraulic fracturing applications while the median grain-size diameter is used to characterize gravel-packing distributions (Table 3).

Sand Grain Morphology (Sphericity and Roundness)

Individual sand grain sphericity and roundness are two particle shape factors that are evaluated when characterizing the proppant potential of a sand. These factors can be qualitatively observed through standard photomicrographs (Plates II & III). Sphericity refers to how closely a particular grain of sand resembles that of a sphere and roundness refers to the corners of an individual sand grain. A sand with high sphericity and roundness is desirable for proppant use. The recommended sphericity and roundness values are 0.6 or greater, with values of 0.7 or greater characteristic of high-strength proppants (API, 2018). Samples tested in this group from deposits in south-central North Dakota had sphericity values generally equal to 0.8 with roundness values ranging between 0.4 to 0.7 (Figure 16). These values approach desired specifications, particularly for sphericity factors, but are slightly more angular in grain character than those found near Hazen-Stanton and Denbigh.

Acid Solubility

The volume of a sand that is soluble in strong acid is an important test of an effective proppant as acid treatments of oil and gas wells are common during completions. API (2018) recommends for proppant sands that no greater than ≤3% (by weight) of 70/140 be soluble in a 12:3 hydrochloric (HCL) or hydrofluoric (HF) acid solution. None of the samples tested were at or below the recommended acid solubility threshold (Figure 17) but are considerably lower than other sand sources tested in North Dakota (Anderson and others, 2019). Acid solubility on these eolian sands ranged from 5.5 to 10.1% (Table 3).

Silt and Clay Fines Testing (Turbidity)

Turbidity tests measure the optical properties of water samples containing suspended sediment and are commonly used to determine the percentage of fine materials (e.g. silts and clays) present. With respect to proppant potential, the turbidity test measures the amount of associated fines within a particular sand sample. It can be used to identify sand sources that require additional washings, etc., during initial processing of raw product into frac-sand. Turbidity is measured and commonly reported in Formazin Turbidity Units (FTU). The recommended limit of frac sand is less than 250 FTU. All 14 samples were below the recommended limit of 250 FTU (Figure 18). The samples ranged from 21.7 to 67.2 FTU (Table 3), generally higher than other windblown sand sources tested (Anderson, 2020a).

Crush Resistance

Sand compositions can be quite variable as can the resultant strength. A crush resistance test measures 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. Crush resistance testing was performed on the material from the largest size class on all 14 samples.

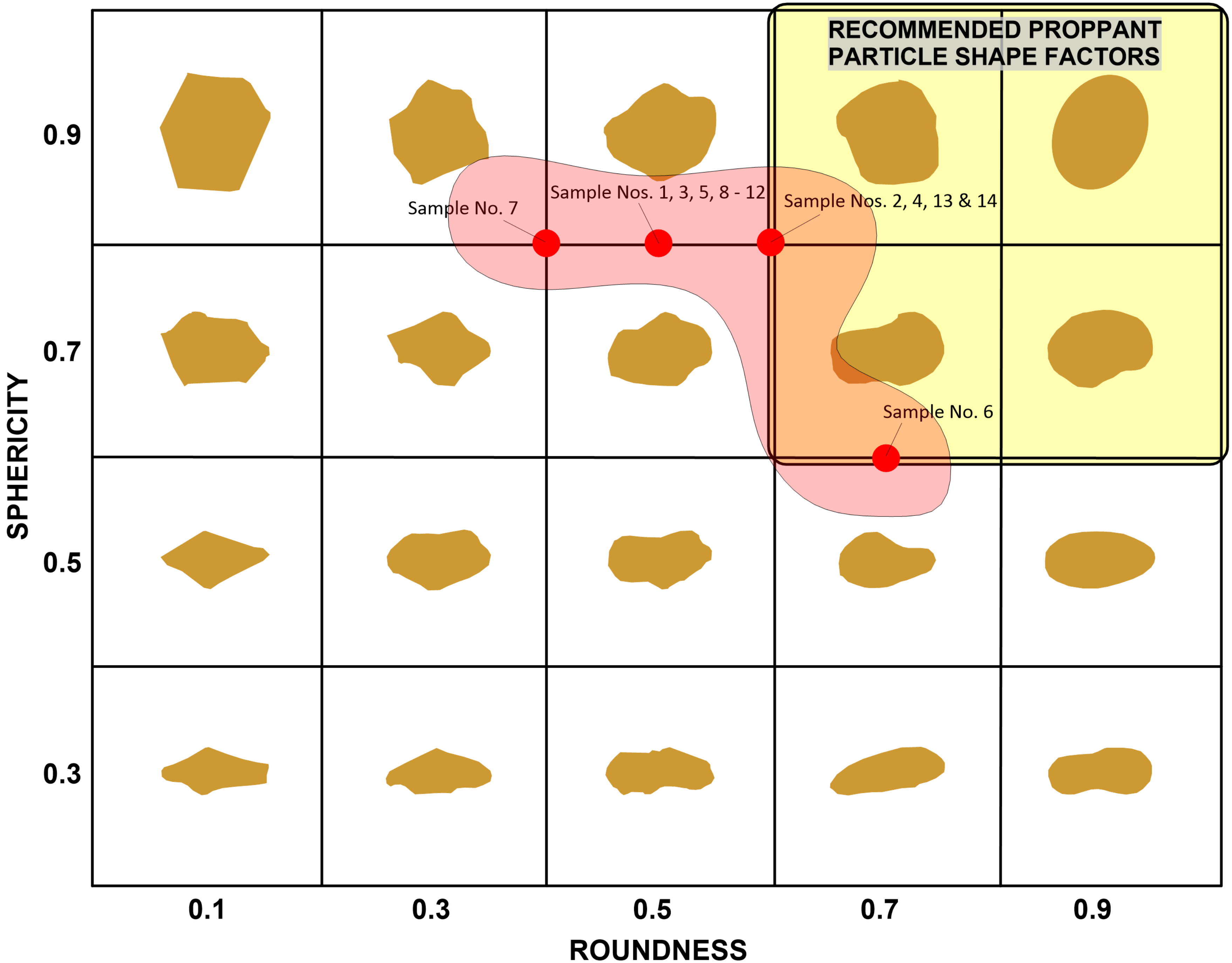

Figure 16. Comparison of sphericity and roundness values for windblown sand samples from south-central North Dakota. Samples from these deposits have particle shape factor values (shaded red) that approach the range of desired specifications (shaded yellow) for frac sand as compared to Ottawa White silica sands.

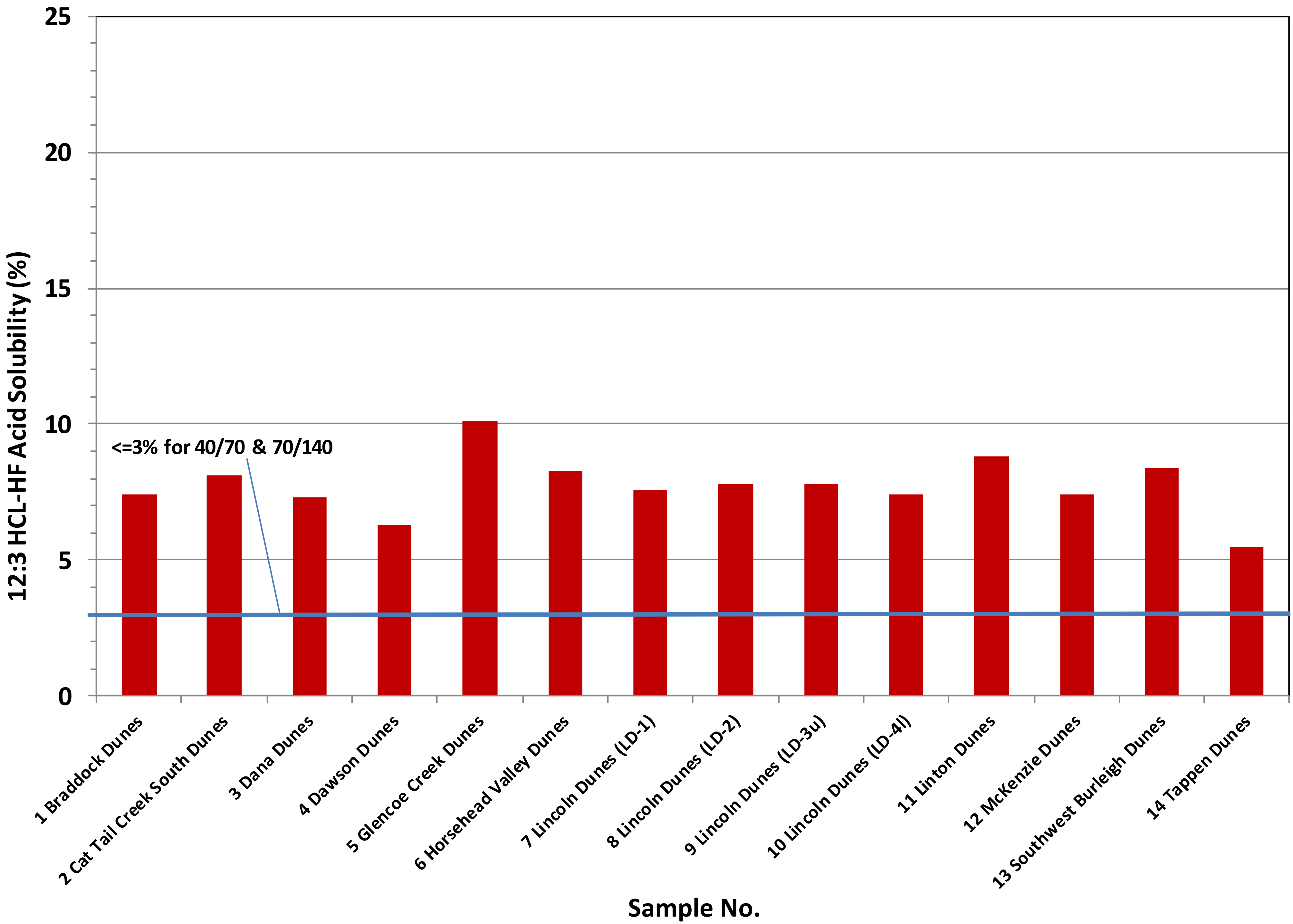

Figure 17. Comparison of hydrochloric:hydrofluoric acid solubility results for windblown sand samples from dune deposits in south-central North Dakota. Recommended specifications for acid solubility on 40/70 & 70/140 sands are less than or equal to 3%.

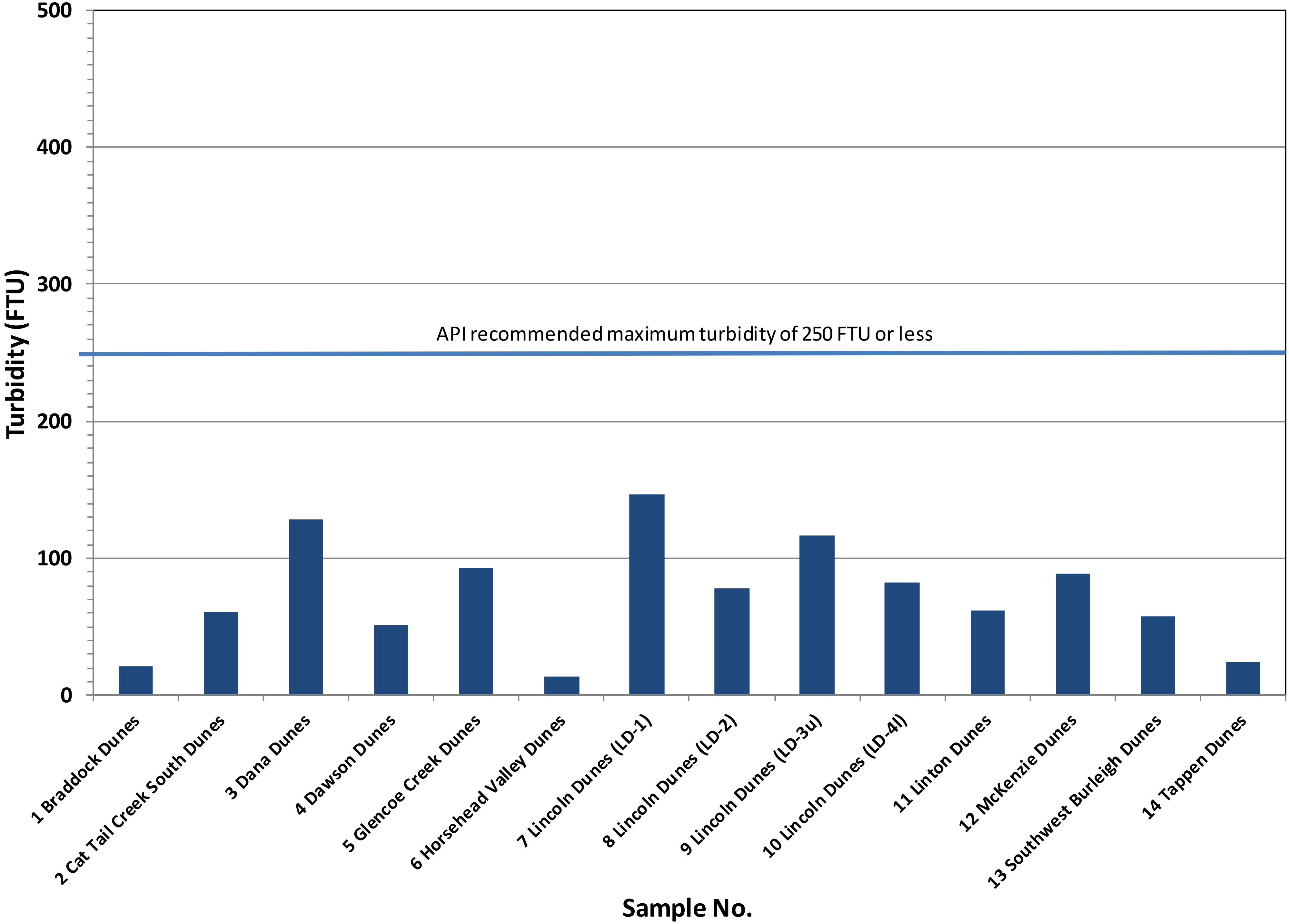

Figure 18. Comparison of turbidity results for washed windblown sand samples from dune deposits in south-central North Dakota. Recommended API specifications for turbidity are 250 FTU or less. All samples tested are well below this value.

K-Values were determined by subjecting the samples to one set of two pre-determined stresses, that were determined by the size range of the samples. A K-value is defined as the highest stress level that will generate no more than 10% crushed material (rounded down to the nearest 1,000 psi). Crush resistance in these samples ranged from 4,000 psi to 5,000 psi (4K to 5K) within the 40/70 and 70/140 size classes (Table 6). Ottawa White sands typically generate K-values between 7 to 15K. Bakken oil and gas wells have fracture closure stresses in the reservoir that range typically around 9,500 psi.

Loss on Ignition Testing

Loss on ignition (LOI) testing was performed on selected sample size cuts in order to serve as a proxy for determination of the potential detrital lignite content. The LOI values were all comparatively low, ranging from 0.23 to 0.95%, which is probably to be expected from a washed, sized sample cut (Table 3, Figure 19).

Mineralogy (X-Ray Diffraction)

Sample geochemistry was determined using qualitative and quantitative X-ray diffraction (XRD) on all washed and sized sand samples reported in weight percent (Table 7). XRD analysis is commonly used to determine the mineralogy of fine-grained lithologies, particularly clays. In general, the samples had similar overall mineralogical compositions with some variability in the lower percentages of feldspars and clays. Quartz percentages ranged from 59 to 75%, feldspar ranged from 26 to 38%, and clay contents ranged from 0 to 3.6% (Figure 20). In comparison, Ottawa White silica sands are commonly 99% quartz. XRD phase diagrams for all samples tested are included in Appendix II. These deposits are generally similar in mineralogical character (Figure A-II-15).

Additional XRD work was performed on several *bulk* sand samples (i.e. meaning samples that have not been washed and sized) in order to provide additional information of overall mineralogical character on deposits in situ (Appendix III). In these analyses clay contents range higher from 2 to 10% as would be expected, and micas were reported also ranging from 2 to 10% (Table A-III-1). No carbonates or iron containing minerals were detected in these samples either, further suggesting a low potential for the existence of potentially deleterious mineralogy to be present in the windblown deposits.

Bulk Density

Regarding proppants, the bulk density describes the mass that fills a unit volume and includes both the proppant and the void space (i.e. porosity) in the sample. It is commonly used in determining the mass of proppants required to fill fractures, a storage vessel, or in completing general volume estimates. The bulk density of these windblown sands (Table 3) ranged from 82 to 91 pounds per cubic foot (pcf) with an average of 85 pcf.

Table 6. Crush Resistance Testing Data Summary

Sample No.	Windblown Sand Area	Tested Size Class	K-Value	Test Stress (psi)					
				3000	4000	5000	6000	7000	8000
				Fines Generated (%)					
1	Braddock Dunes	70/140	5K	--	--	8.36	10.86	--	--
2	Cat Tail Creek South Dunes	40/70	5K	--	--	9.43	11.79	--	--
3	Dana Dunes	70/140	5K	--	--	8.62	12.16	--	--
4	Dawson Dunes	40/70	5K	--	--	7.71	10.58	--	--
5	Glencoe Creek Dunes	70/140	4K	--	9.44	12.70	--	--	--
6	Horsehead Valley Dunes	70/140	4K	--	8.94	11.49	14.07	--	--
7	Lincoln Dunes (LD-1)	70/140	5K	--	--	8.66	11.85	--	--
8	Lincoln Dunes (LD-2)	70/140	4K	--	6.65	10.39	--	--	--
9	Lincoln Dunes (LD-3u)	70/140	5K	--	--	8.57	10.82	--	--
10	Lincoln Dunes (LD-4l)	70/140	5K	--	--	9.79	12.47	--	--
11	Linton Dunes	70/140	4K	--	--	8.62	11.79	--	--
12	McKenzie Dunes	70/140	5K	--	--	8.95	11.84	--	--
13	Southwest Burleigh Dunes	40/70	4K	--	8.71	12.62	--	--	--
14	Tappen Dunes	40/70	5K	--	--	8.21	11.87	--	--

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.

-- *Stress point not tested.*

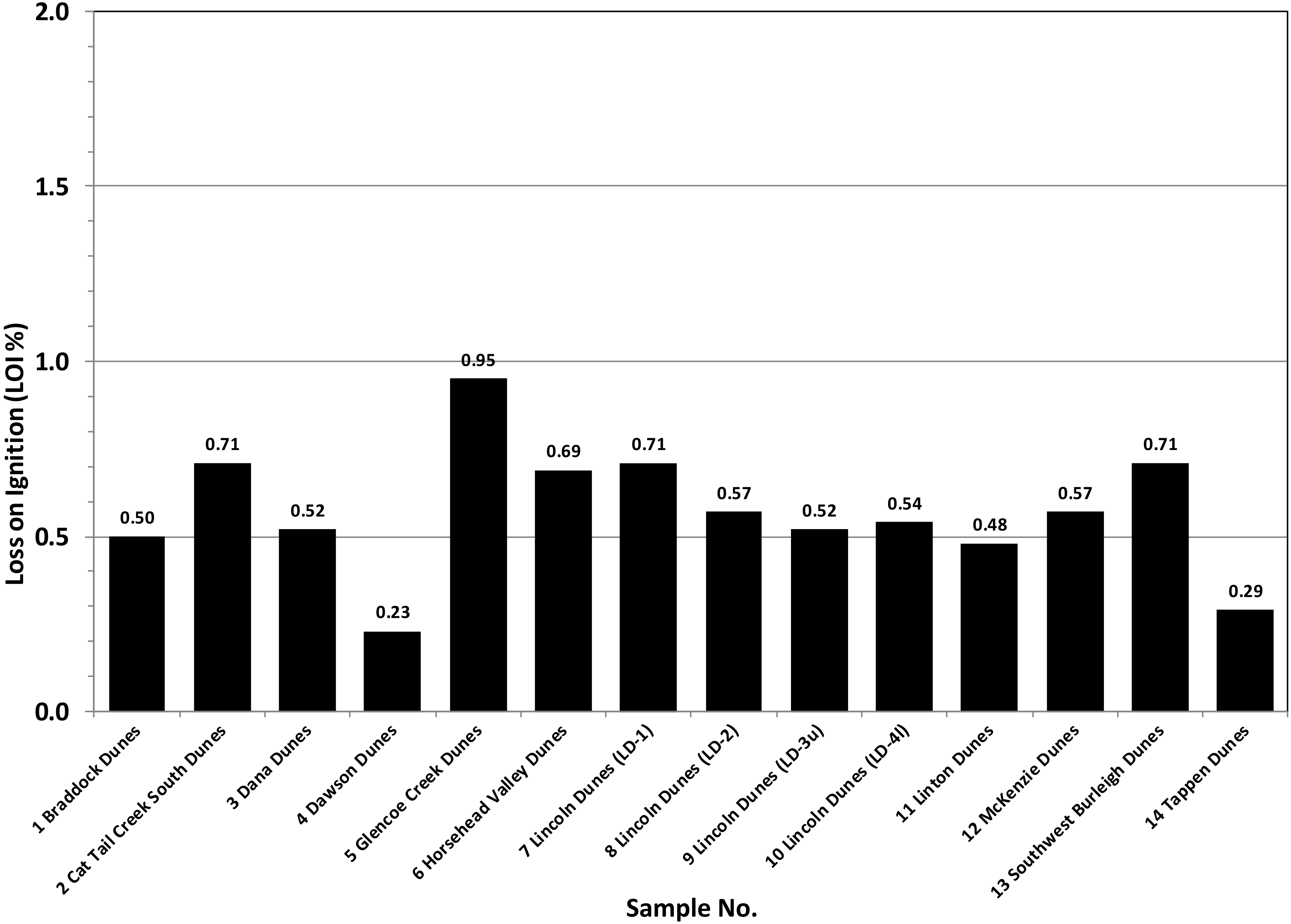

Figure 19. Graph of loss on ignition (LOI) of windblown sand from dune deposits in south-central North Dakota. These sands are from the 40/70 and 70/140 size classes which are washed samples. The majority of samples are all less than 0.5 % LOI which suggests a low overall organic content of material such as detrital lignite.

Table 7. X-ray diffraction (XRD) Mineralogy Analytical Summary

Sample ID	Dune Deposit	Tested Size Class	Quartz	Feldspars			Clays		Carbonates			Other Minerals
				Albite	Microcline	Feldspars*	Illite	Clays*	Calcite	Dolomite	Carbonates*	Chlorites**
1	Braddock	70/140	67.33	16.73	12.53	29.26	3.40	3.40	--	--	--	--
2	Cat Tail Creek South	40/70	71.02	14.75	11.28	26.03	2.08	2.08	--	--	--	0.87
3	Dana	70/140	66.76	17.92	11.50	29.42	3.30	3.30	--	--	--	0.52
4	Dawson	40/70	72.15	13.34	12.75	26.09	0.84	0.84	--	--	--	0.91
5	Glencoe Creek	70/140	65.94	19.89	9.47	29.36	3.59	3.59	--	--	--	1.12
6	Horsehead Valley	70/140	64.00	16.80	19.20	36.00	--	--	--	--	--	--
7	Lincoln (LD-1)	70/140	75.21	21.17	10.85	32.02	2.11	2.11	--	--	--	1.59
8	Lincoln (LD-2)	70/140	65.00	18.88	13.82	32.70	2.30	2.30	--	--	--	2.30
9	Lincoln (LD-3u)	70/140	66.17	16.92	11.89	28.81	5.02	5.02	--	--	--	--
10	Lincoln (LD-4l)	70/140	69.73	15.19	11.68	26.87	3.41	3.41	--	--	--	--
11	Linton	70/140	58.93	26.76	10.79	37.55	2.98	2.98	--	--	--	0.54
12	McKenzie	70/140	68.10	16.74	11.93	28.67	2.14	2.14	--	--	--	1.10
13	Southwest Burleigh	40/70	71.76	16.47	9.40	25.87	1.69	1.69	--	--	--	0.68
14	Tappen	40/70	72.23	15.54	10.28	25.82	1.94	1.94	--	--	--	--

** Undifferentiated*

*** Chiefly Chamosite*

-- Mineral not detected

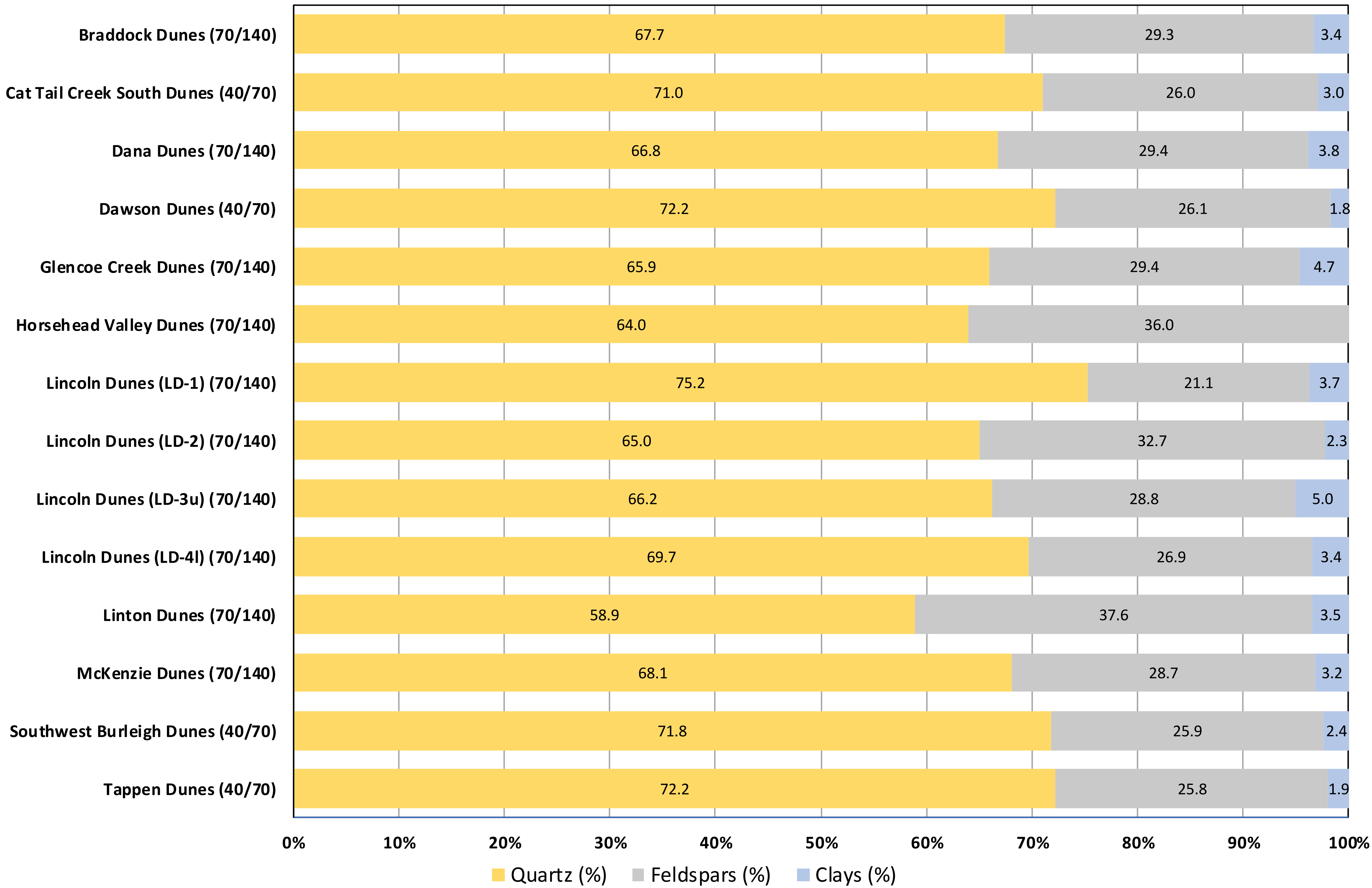

Figure 20. Summary mineralogy (weight %) of processed (washed and sized) sand from X-ray diffraction (XRD) analysis of windblown sand deposits in south-central North Dakota. No carbonates were reported in any of the samples analyzed.

Absolute (particle) density

The absolute density or particle density of a sand measures the density by way of pycnometric (gas displacement) methods. The absolute density of the tested eolian sands ranged from 1.5 to 1.7 grams per cubic centimeter (g/cm^3) with an average of 1.6 g/cm^3 (Table 2). Absolute density values are used in the design of hydraulic fracturing applications. A brief summary of proppant testing specifications is provided in Appendix IV.

CONCLUSIONS

Windblown sand deposits in south-central North Dakota have geologic characteristics that approach the standards and specifications for use as proppant based on current industry requirements but are of lesser overall quality than sands found in the Hazen-Stanton and Denbigh Dunes. These deposits are found in low and high-relief sand dunes occurring in localized coalesced dune fields in eleven separate areas. The sand is well sorted with sand grain size ranges dominantly in the finer size classes (40/70 & 70/140) and contain an average of 68% quartz in the washed and sized sand portion. Crush-resistance testing typically ranges from 4,000 to 5,000 psi (4K to 5K) in the 40/70 and 70/140 sand sizes. Particle shape factors for these sand grains also approach desired industry specifications for sphericity and roundness but are slightly lower than deposits in Mercer and McHenry Counties. Sand deposit quality appears to be greatest within deposits found along the Burleigh\Kidder and Emmons County borders. Additional material processing would likely be needed to increase favorable testing results for these sands and will continue to be evaluated. The testing data included in this report should prove valuable for other potential industrial sand uses as well as future sedimentological research in eolian environments.

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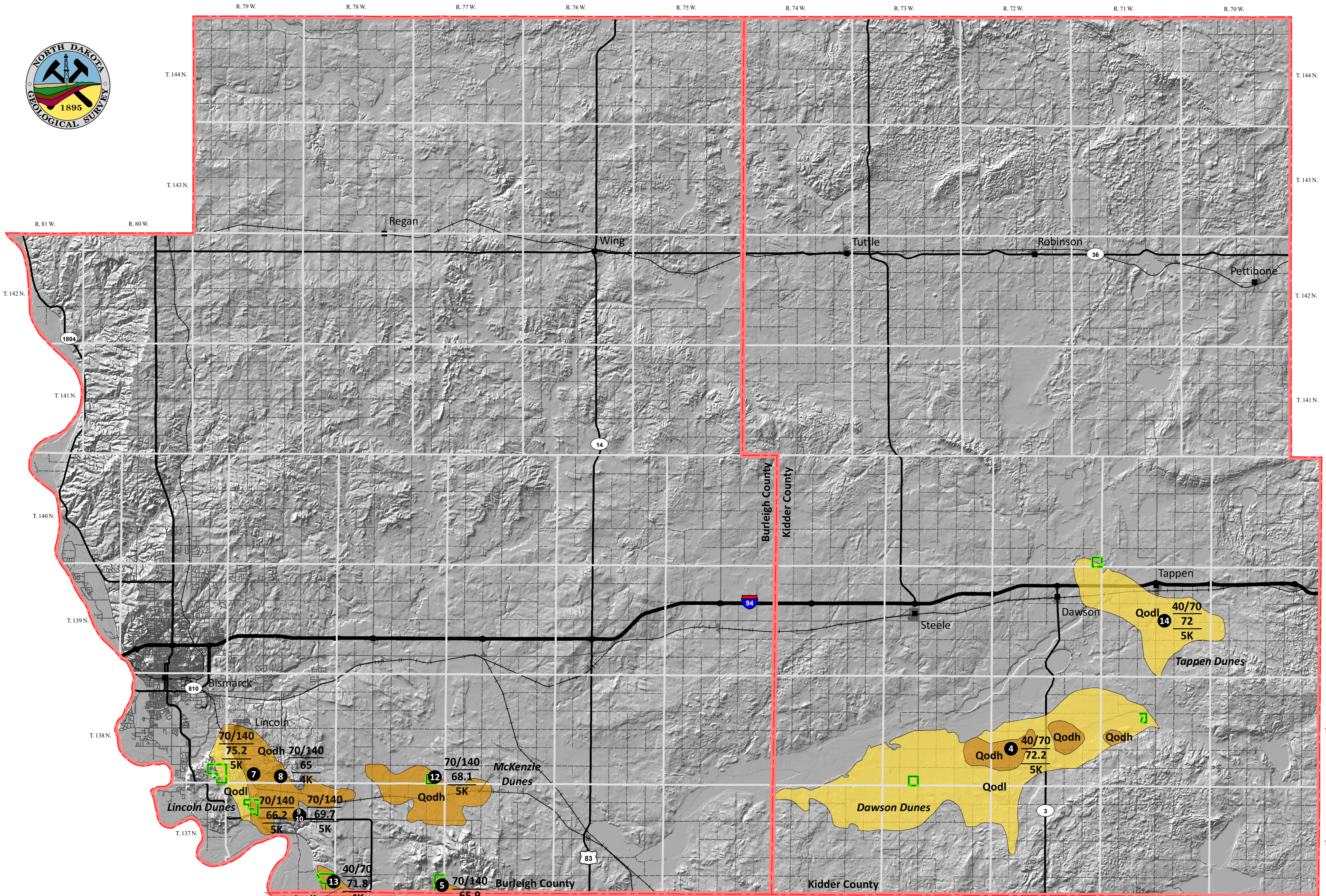
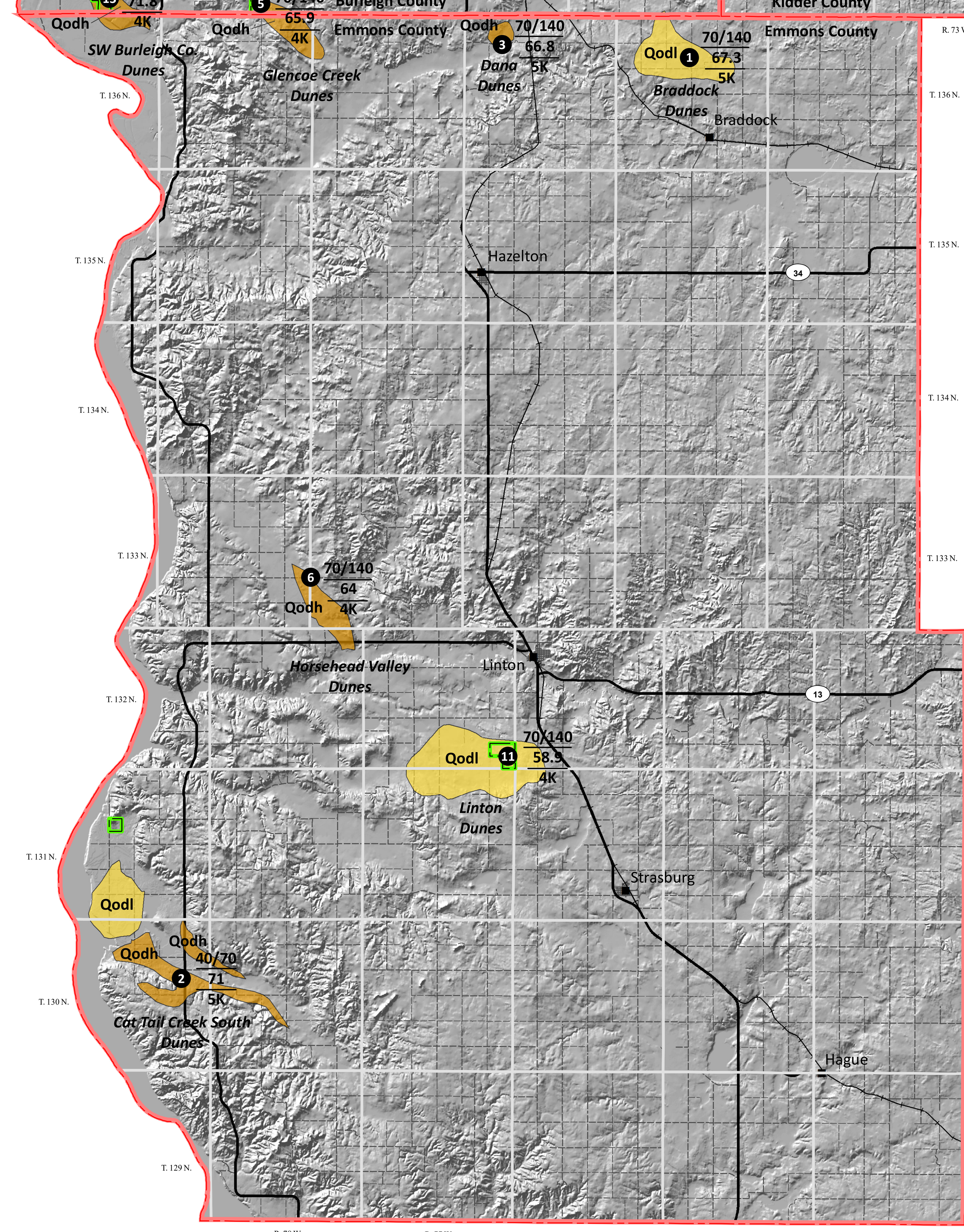
North Dakota Geological Survey
Report of Investigation No. 126 - Plate I

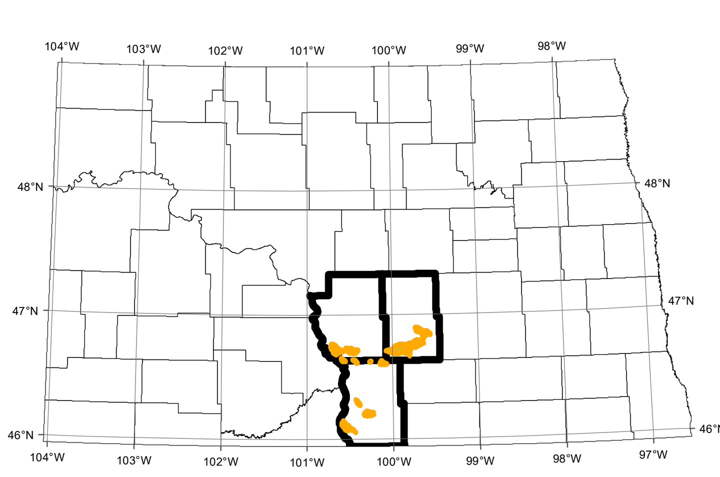
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Reources

Windblown Sand Deposits in South-Central North Dakota

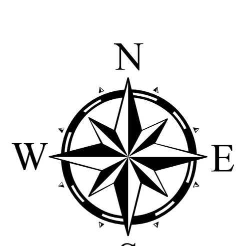




Names	acres	sq. miles
Braddock Dunes	3,682.66	5.75
Cat Tail Creek South Dunes	4,004.14	6.26
Dana Dunes	475.09	0.74
Dawson Dunes	46,638.70	72.87
Glencoe Creek Dunes	1,802.48	2.82
Horsehead Valley Dunes	1,917.11	3.00
Lincoln Dunes	13,454.99	21.02
Linton Dunes	7,267.52	11.36
McKenzie Dunes	8,632.46	13.49
SW Burleigh Co. Dunes	1,739.06	2.72
Tappen Dunes	13,664.89	21.35



Windblown Sand Deposits, South-Central North Dakota



Scale 1:250,000

0 5 10

Miles

Mercator Projection
North American 1983 Datum
Central Meridian 101°7'30"W
Standard Parallel 1: 46°37'30"N

DISCUSSION

Windblown sand deposits in south-central North Dakota cover approximately 167.5 square miles (107,224 acres) and were evaluated in a reconnaissance manner in 2019 and 2020 in support of the exploration for potential sources of in-basin proppant sand for hydraulic fracturing of oil wells in the Williston Basin. A total of 14 samples were collected from 11 dune fields within southwestern Burleigh County, southern Kidder County and northern and southwestern Emmons County. Samples were collected from high-relief dune fields and areas of gently undulating sheet sands with occasional low-relief dunes. Some of these deposits may have potential to be suitable for proppant use based on current industry requirements.

EXPLANATION

Windblown Sand Deposits

Qodh — Windblown sand in dune fields of high relief commonly greater than 30 feet (10 m) and up to 60 feet (18.3 m).

Qodl — Windblown sand in low-relief dunes typically less than 10 feet (3 m) in height along with wind-scoured areas with thin tabular sheet sands draping pre-existing topography.

● Samples collected and tested for proppant use.

Surface Trust Land

Other Features

Highways — County Boundaries — Railroad — County Roads

Sample Location — 11 — 70/140 — Tested Size Class; 58.9 — Quartz Content (wt%); 4K — Crush Resistance (K-value)

MAP COMPILATION REFERENCES

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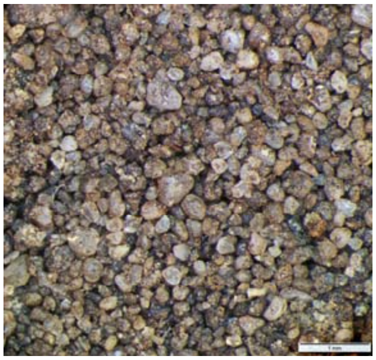
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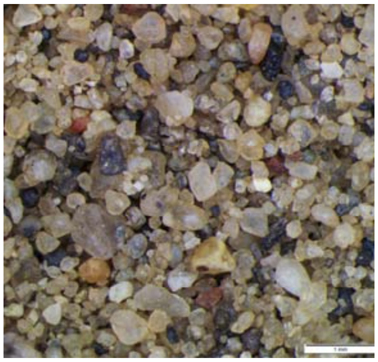
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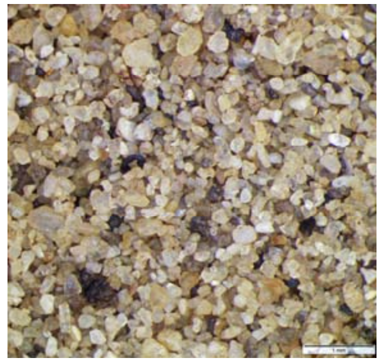
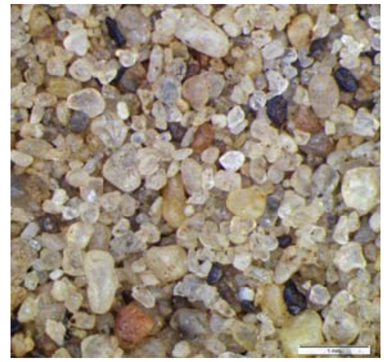
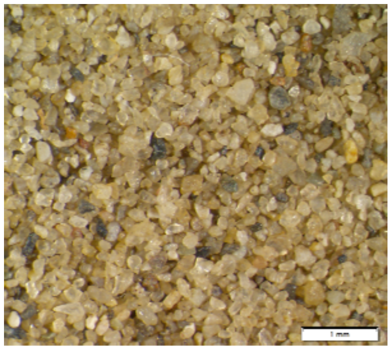
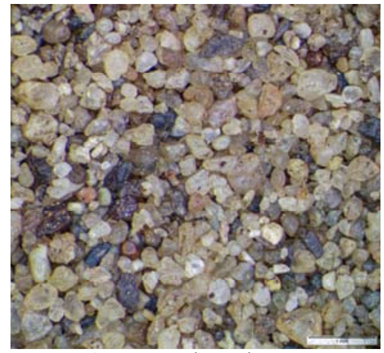

3. Dana Dunes

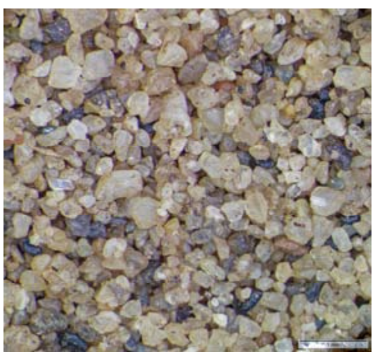

4. Dawson Dunes

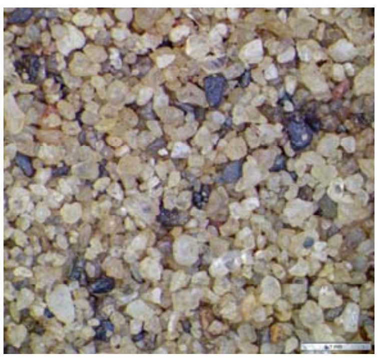

5. Glencoe Creek Dunes

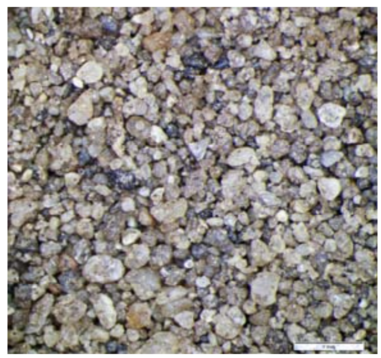

6. Horsehead Valley Dunes

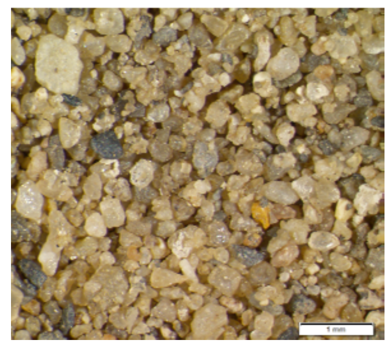

7. Lincoln Dunes (LD-1)


8. Lincoln Dunes (LD-2)

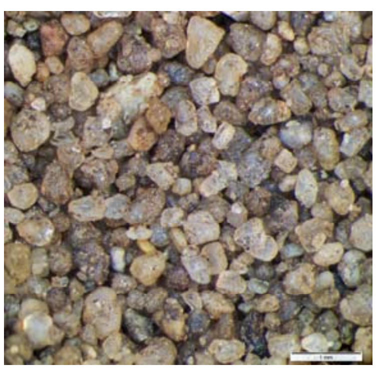

9. Lincoln Dunes (LD-3u)


10. Lincoln Dunes (LD-4l)


11. Linton Dunes


12. McKenzie Dunes


13. Southwest Burleigh Co. Dunes


14. Tappen Dunes


Ottawa "White" Sand

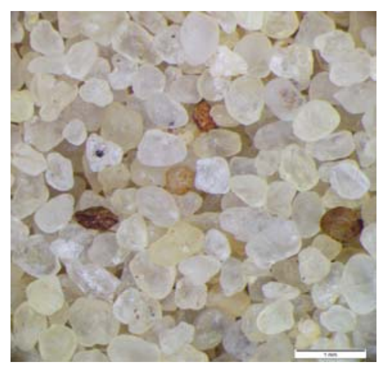
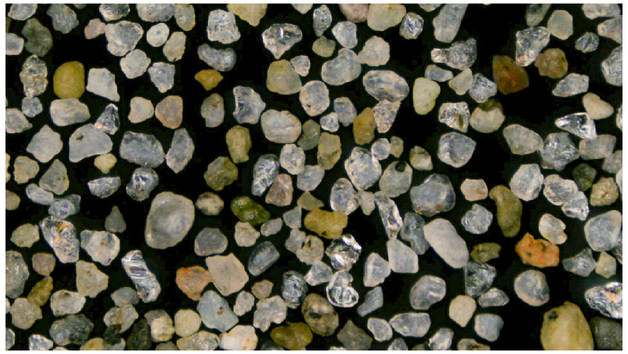

Brady "Brown" Sand

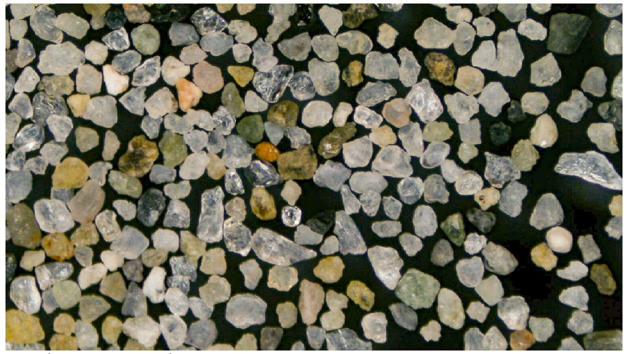
Plate II. Bulk sand photomicrographs (25X) of windblown sand from dune deposits in south-central North Dakota. Two examples of other common proppant sands (Ottawa White and Brady Brown) are also included for comparison.

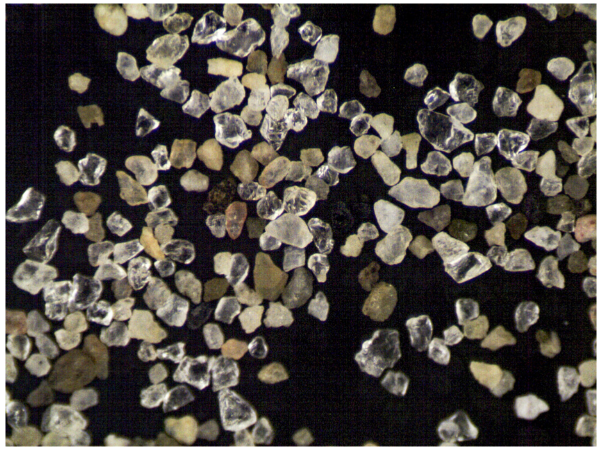

1. Braddock Dunes

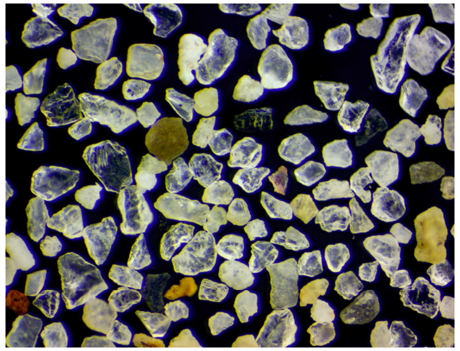

2. Cat Tail Creek South Dunes

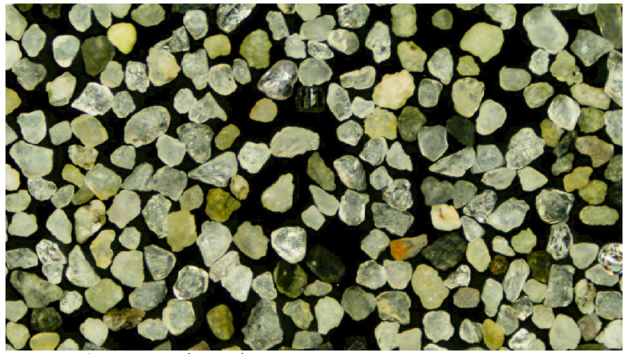

3. Dana Dunes

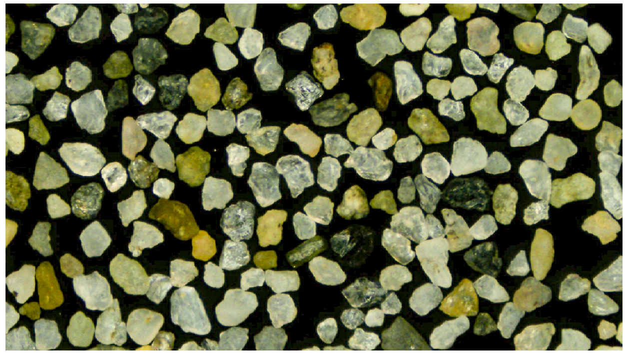

4. Dawson Dunes


5. Glencoe Creek Dunes

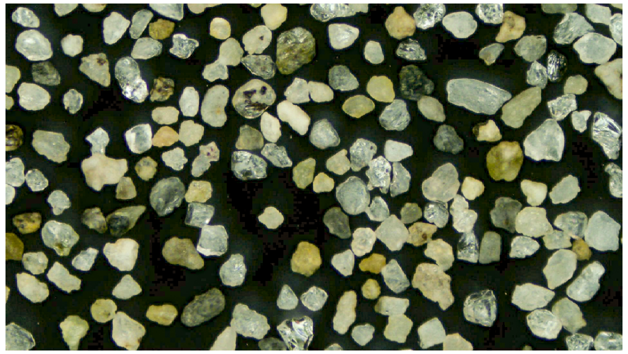

6. Horsehead Valley Dunes


7. Lincoln Dunes (LD-1)


8. Lincoln Dunes (LD-2)


9. Lincoln Dunes (LD-3u)


10. Lincoln Dunes (LD-4l)


11. Linton Dunes


12. McKenzie Dunes


13. Southwest Burleigh Co. Dunes


14. Tappen Dunes

Plate II. Monolayer photomicrographs (40x) of windblown sand from dune deposits in south-central North Dakota.

Appendix I. Individual Grain-Size Distribution (Sieve) Diagrams of Windblown Sand Samples from Dune Deposits in South-Central North Dakota.

The gradation diagrams included in this appendix are presented in a traditional Unified Soil Classification System (USCS) style diagram along with Wentworth particle size classifications.

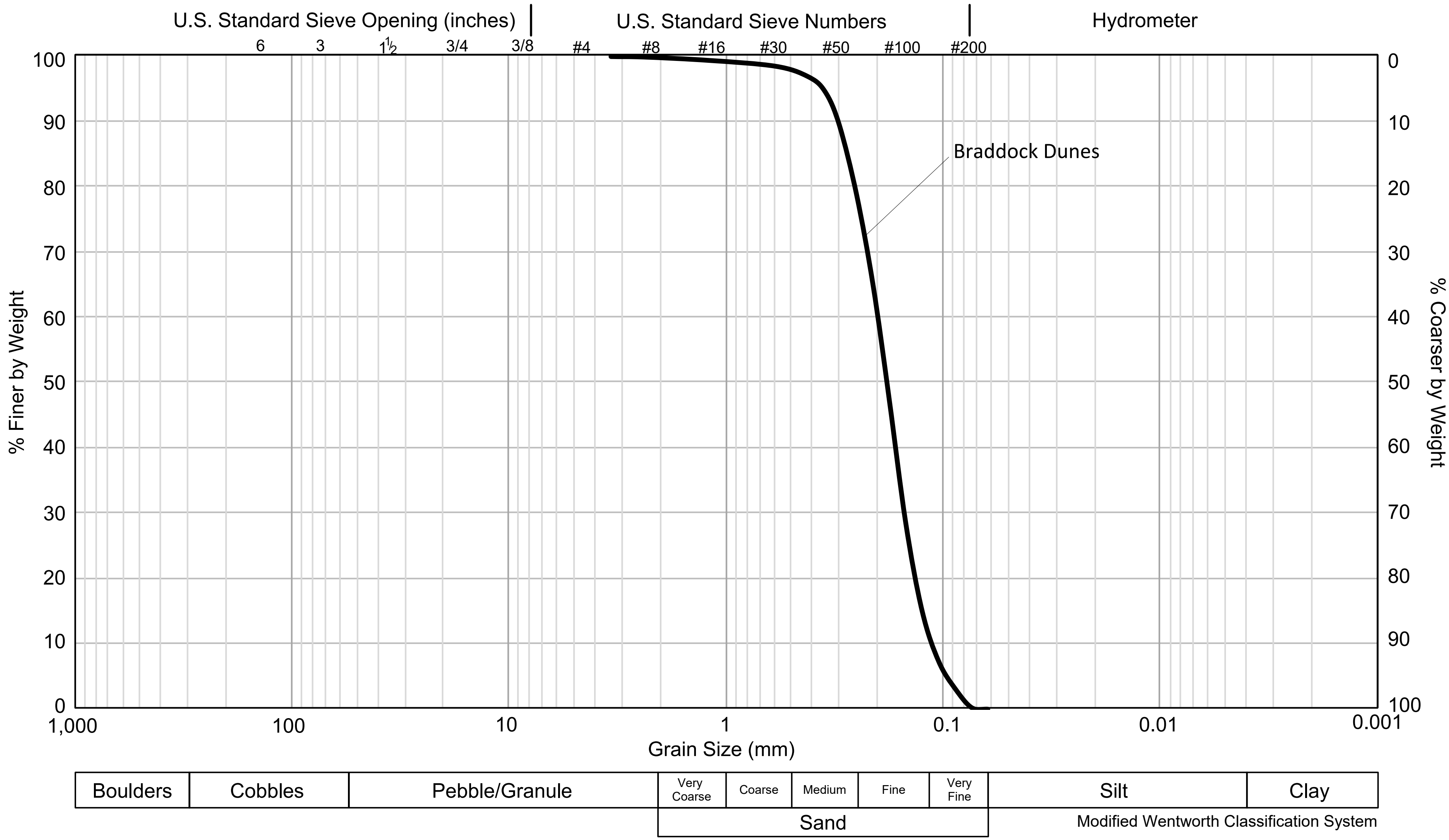


Figure A-I-1. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 1 from the Braddock Dunes.

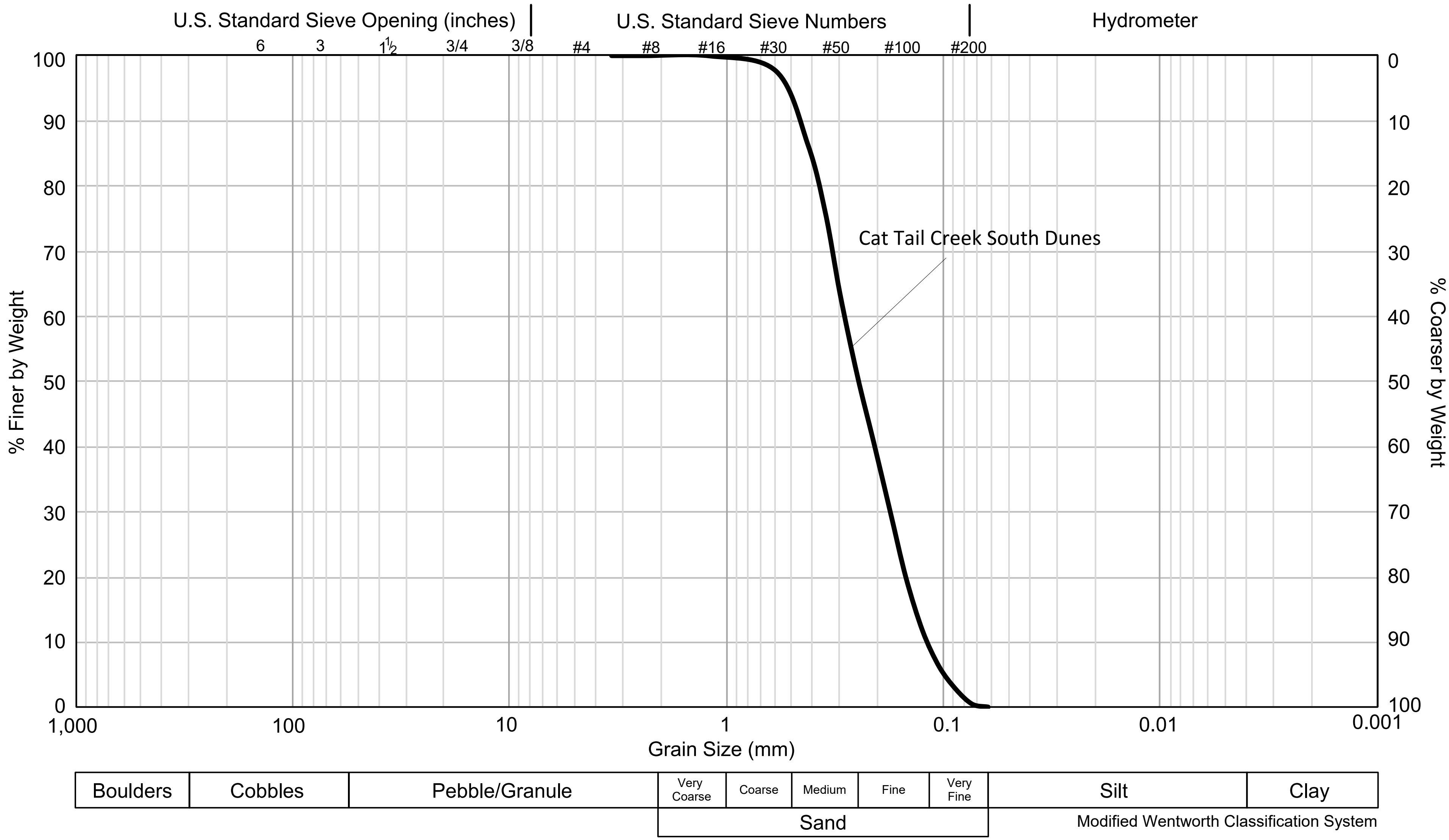


Figure A-I-2. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 2 from the Cat Tail Creek South Dunes.

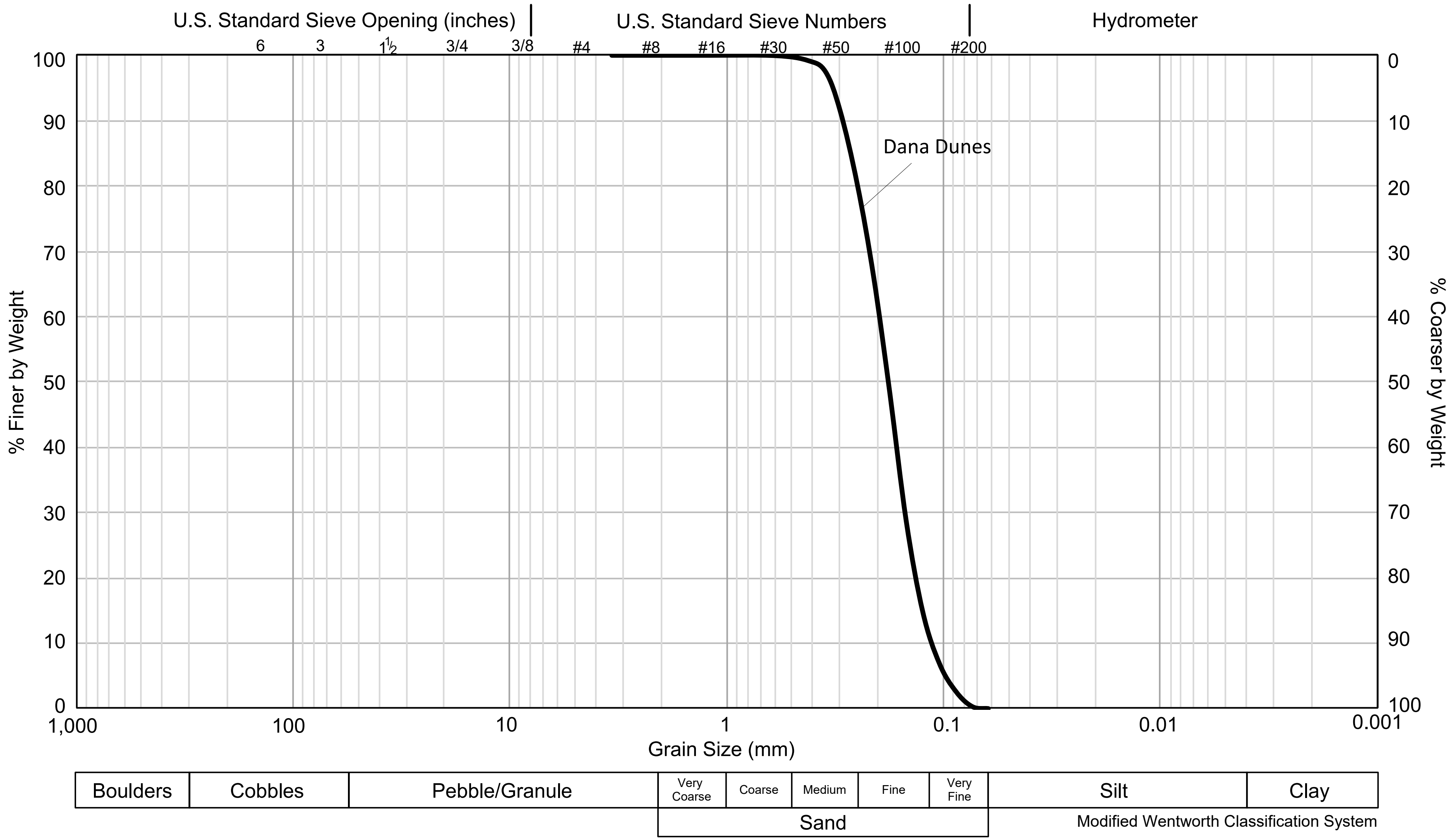


Figure A-I-3. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 3 from the Dana Dunes.

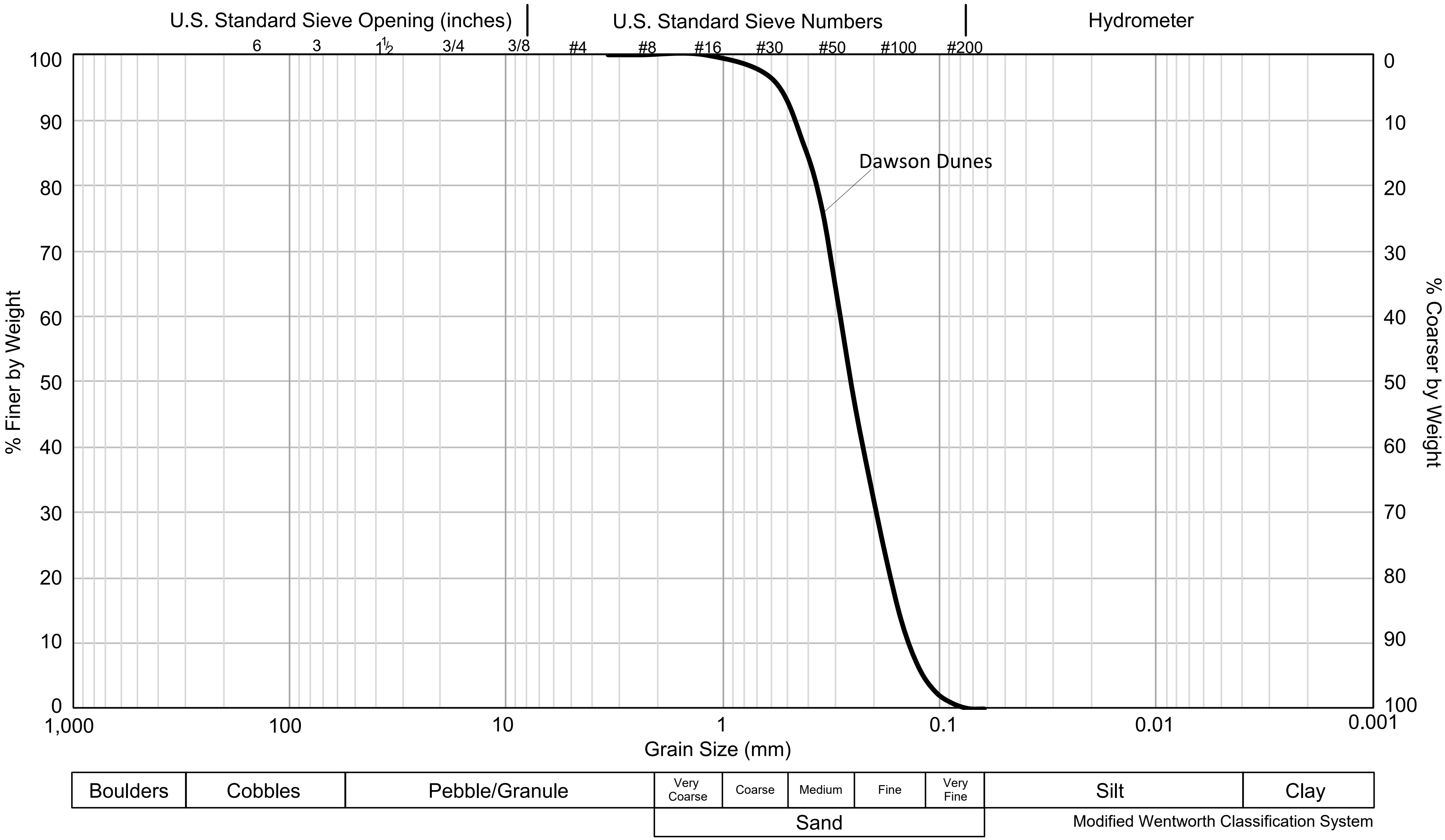


Figure A-I-4. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 4 from the Dawson Dunes.

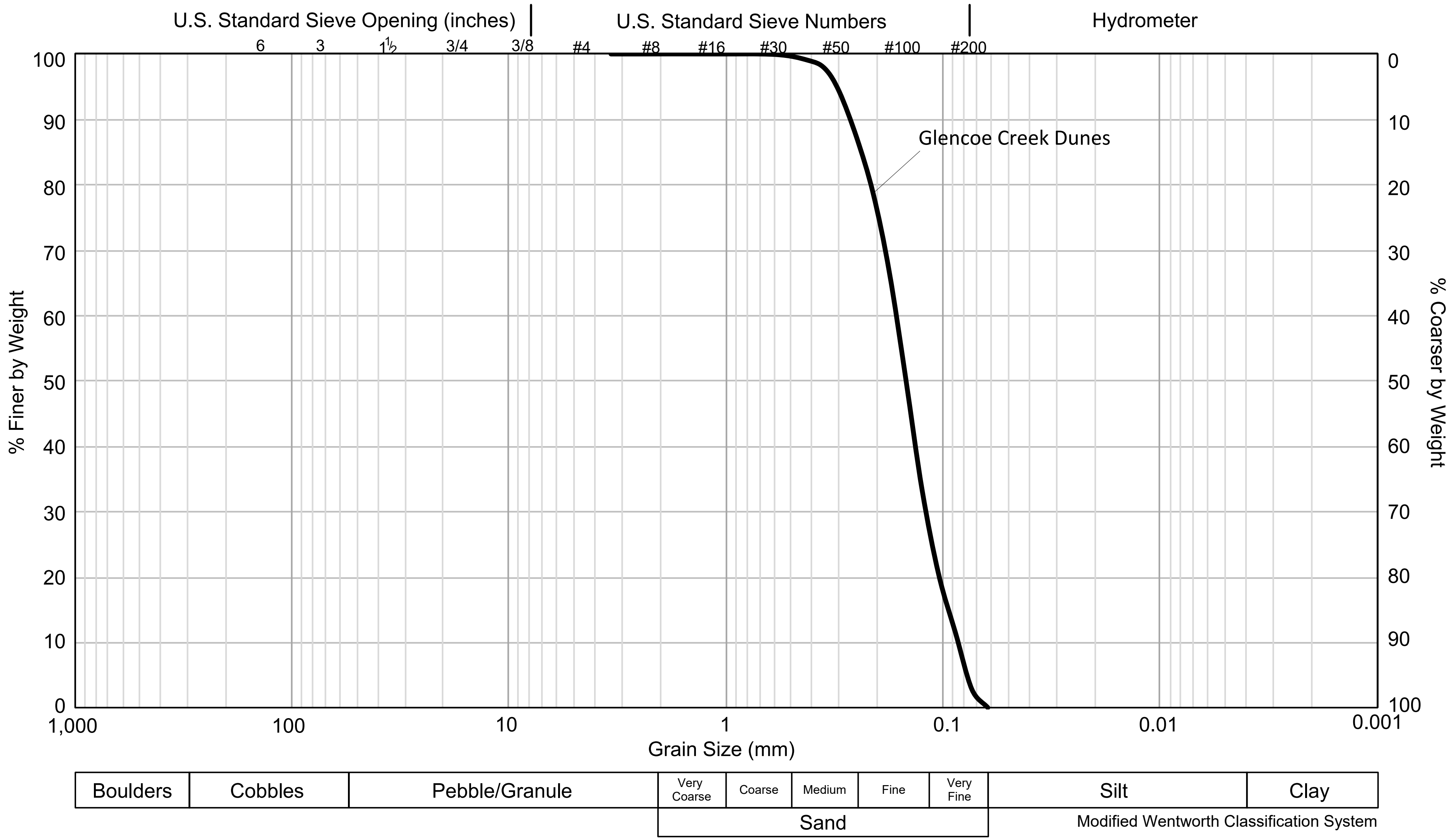


Figure A-I-5. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 5 from the Glencoe Creek Dunes.

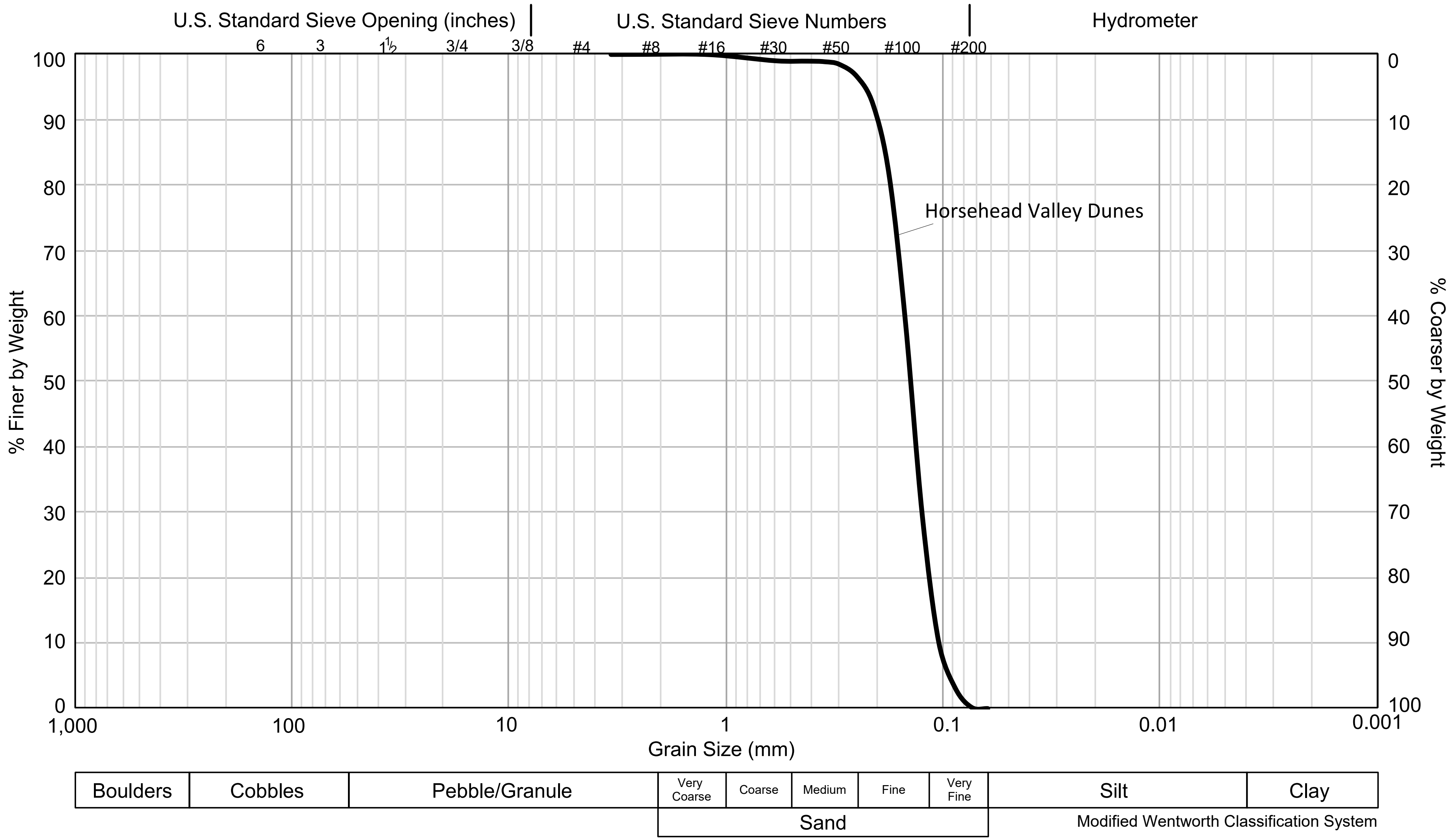


Figure A-I-6. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 6 from the Horsehead Valley Dunes.

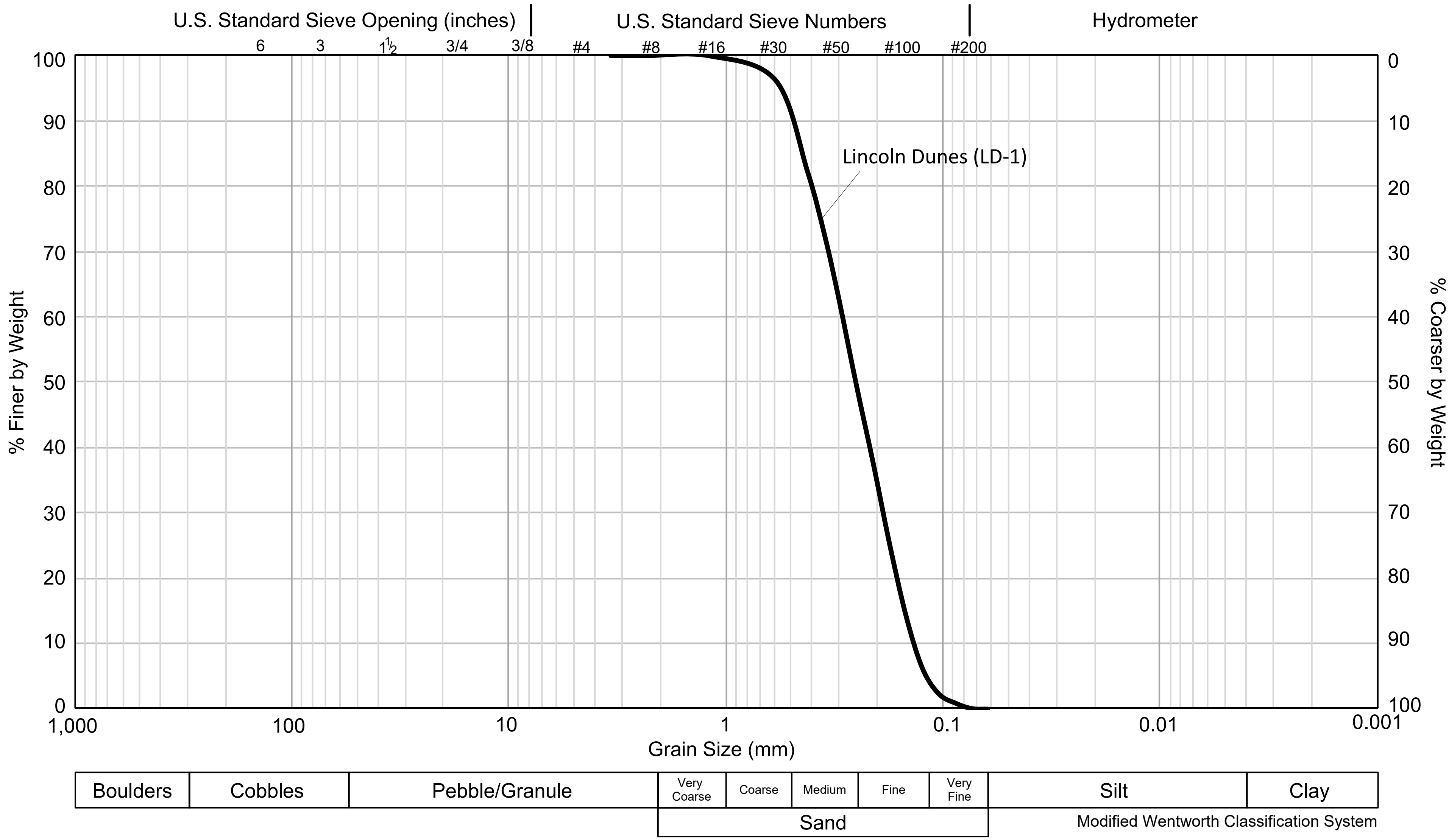


Figure A-I-7. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 7 from the Lincoln Dunes (LD-1).

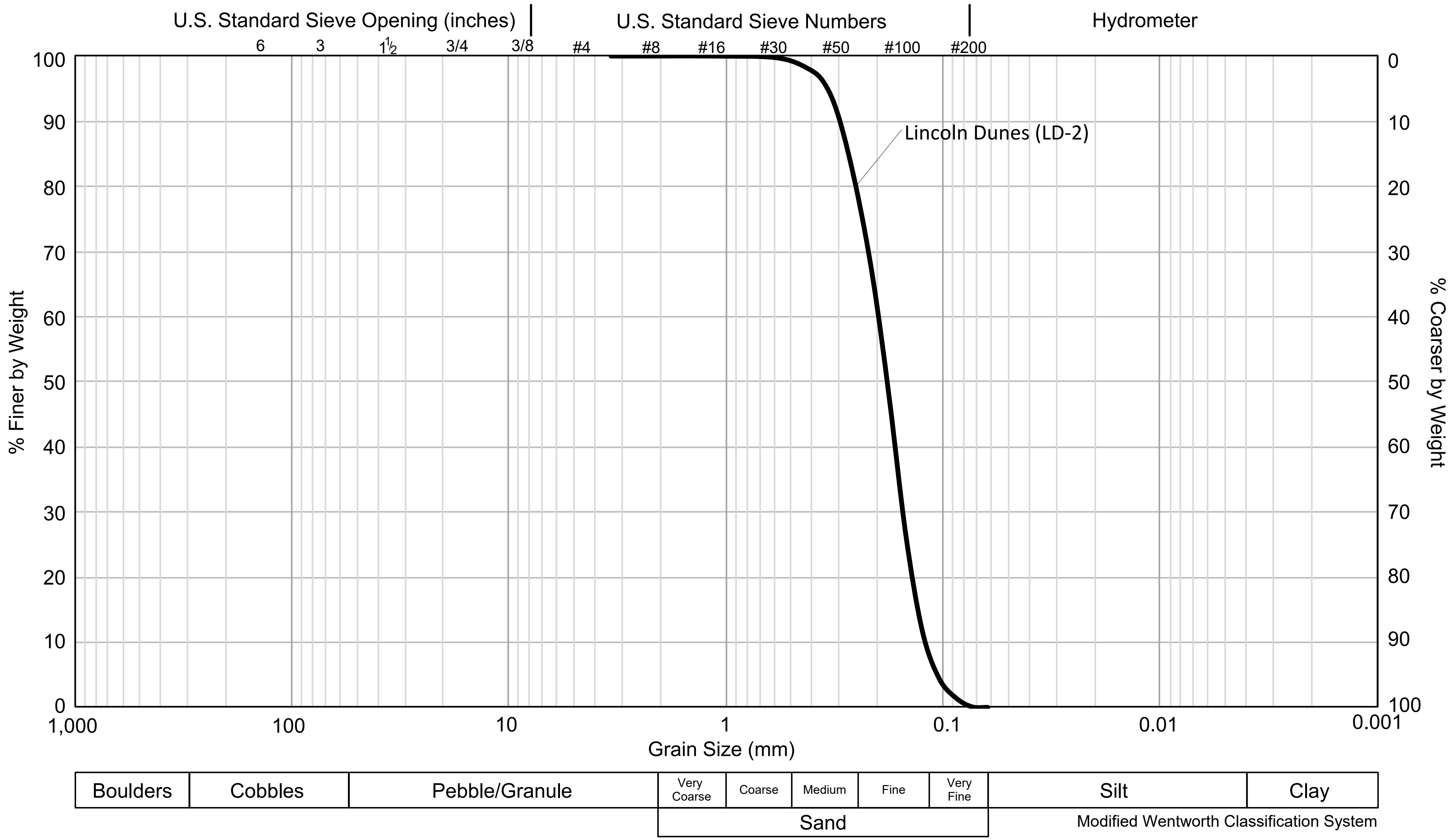


Figure A-I-8. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 8 from the Lincoln Dunes (LD-2).

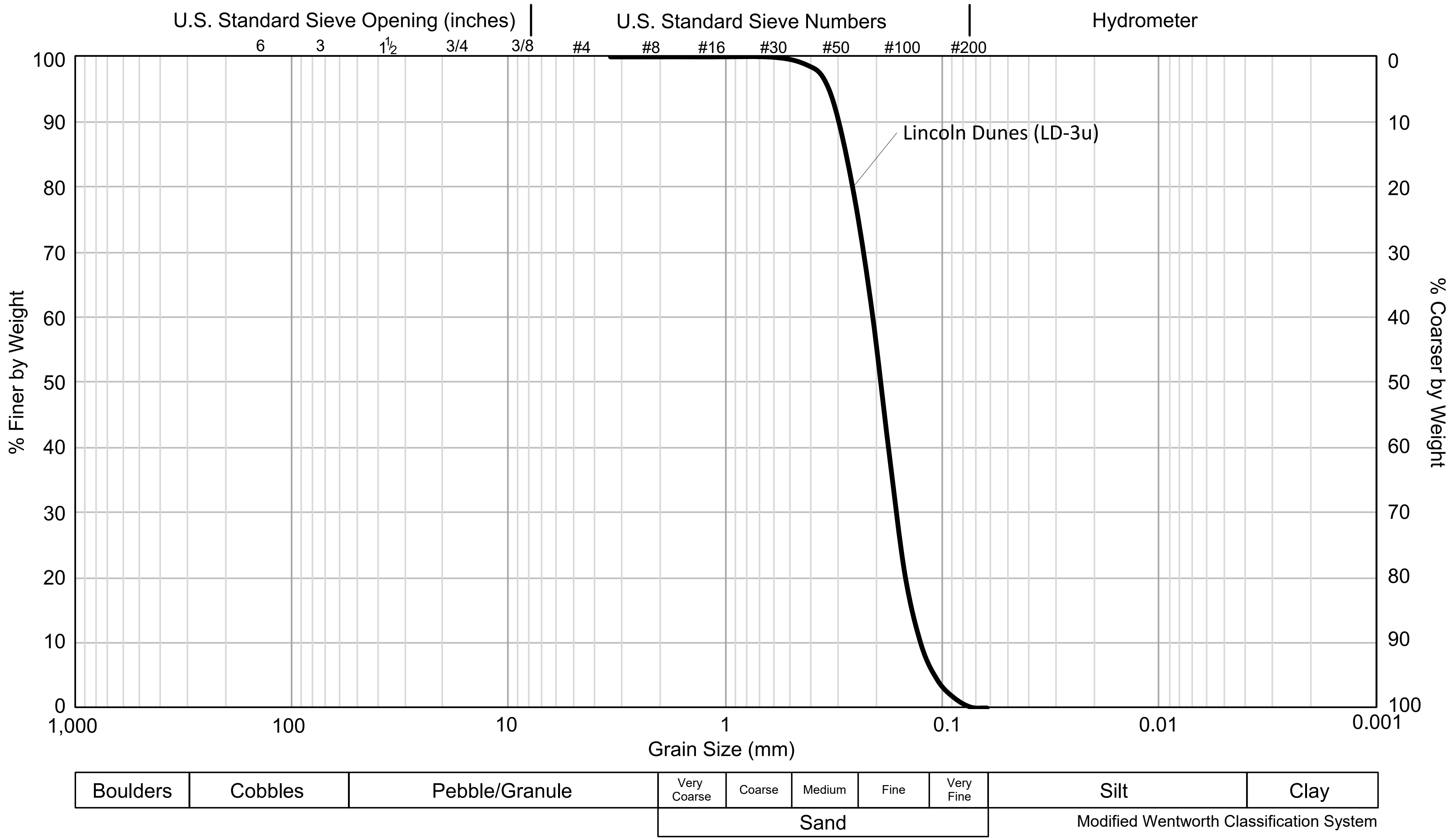


Figure A-I-9. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 9 from the Lincoln Dunes (LD-3u).

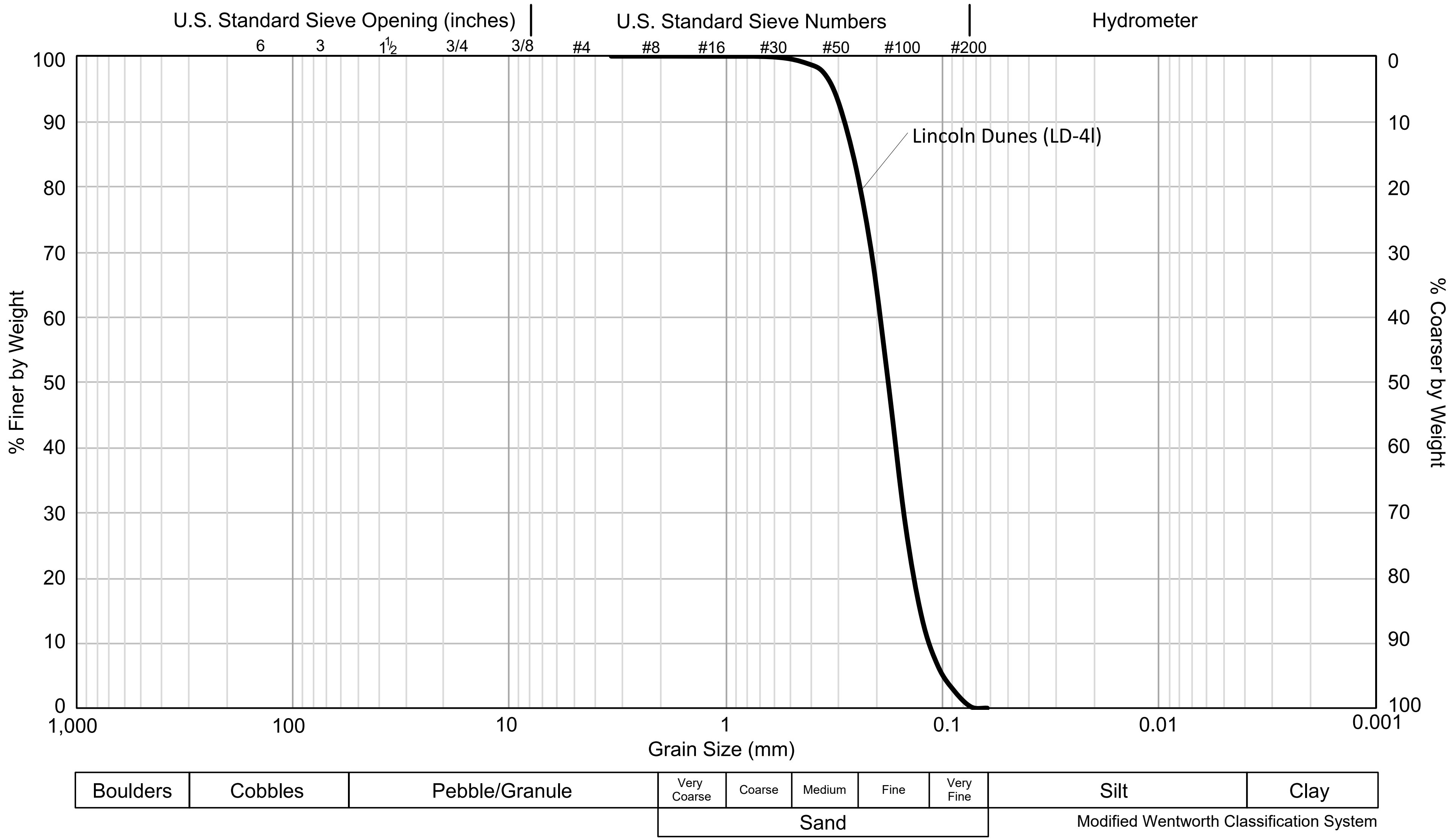


Figure A-I-10. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 10 from the Lincoln Dunes (LD-4l).

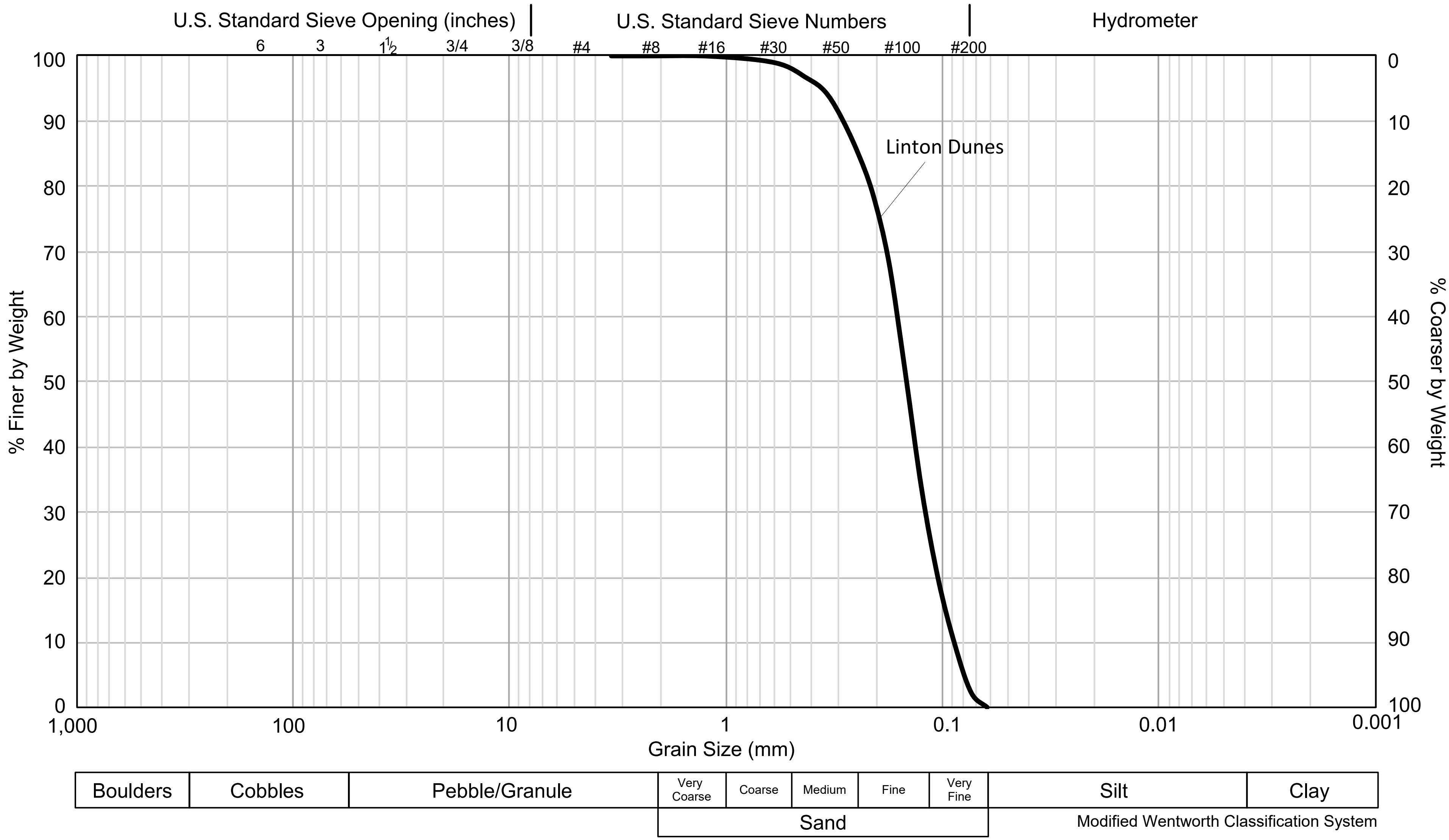


Figure A-I-11. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 11 from the Linton Dunes.

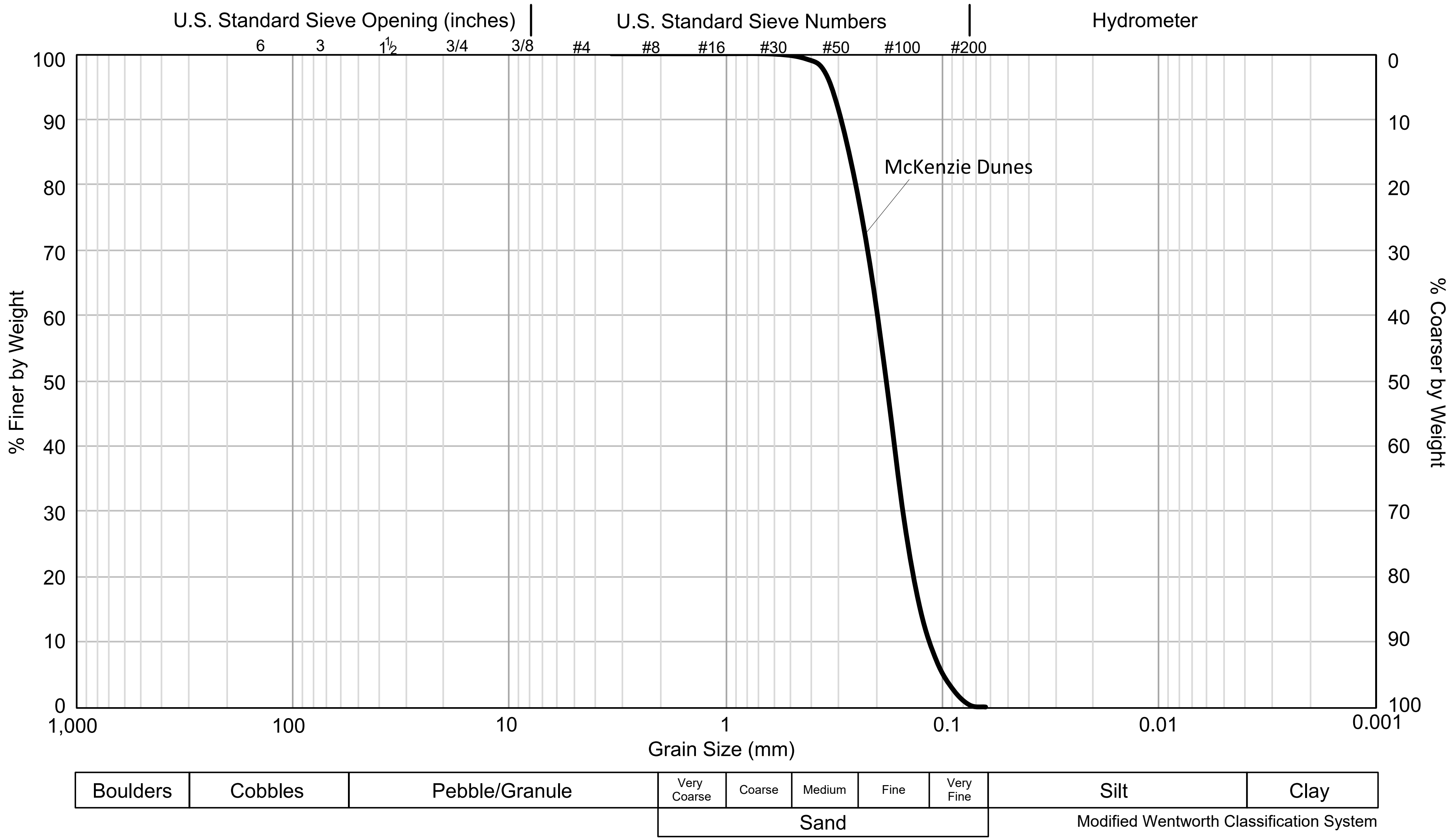


Figure A-I-12. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 12 from the McKenzie Dunes.

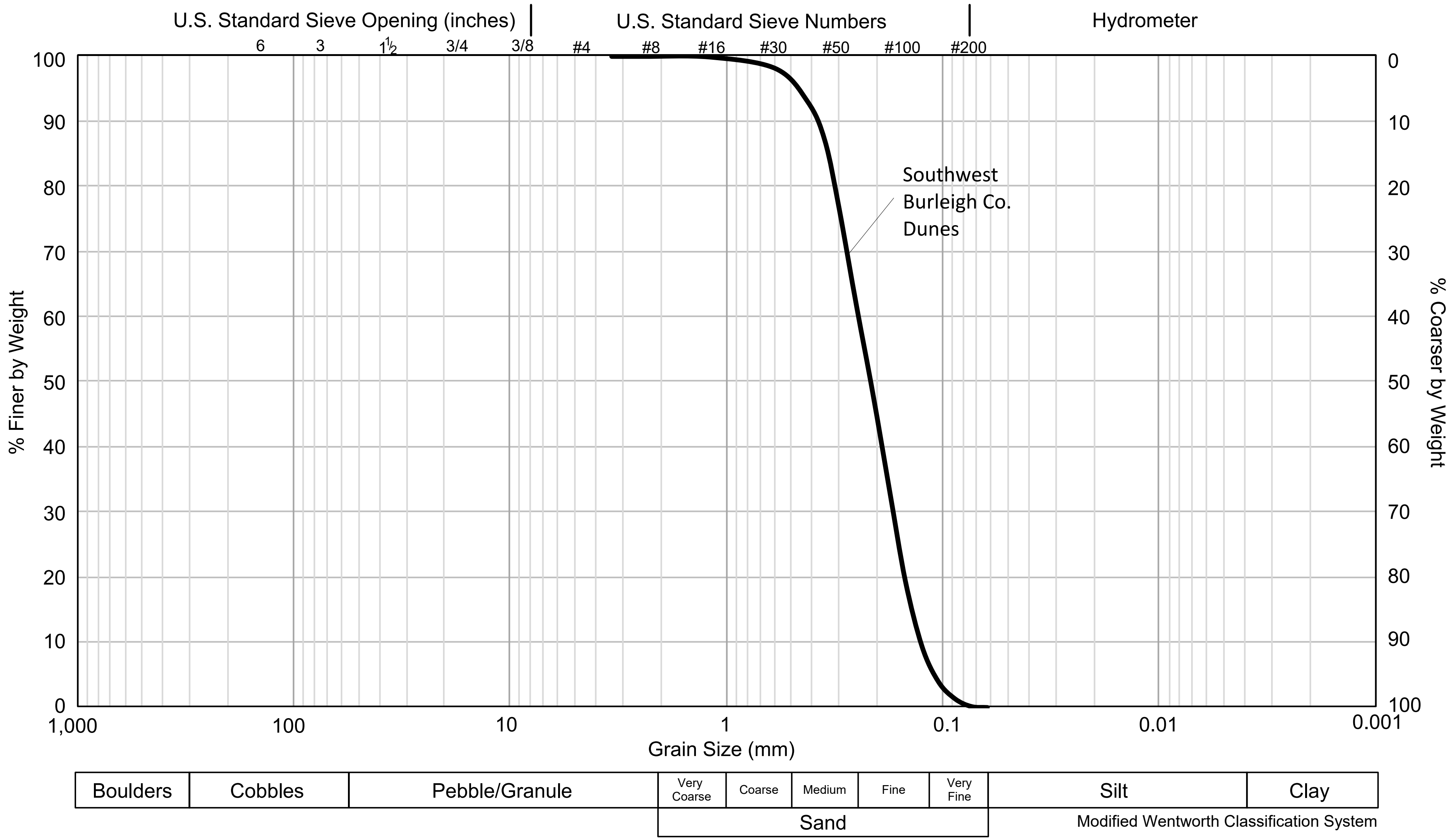


Figure A-I-13. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 13 from the Southwest Burleigh Dunes.

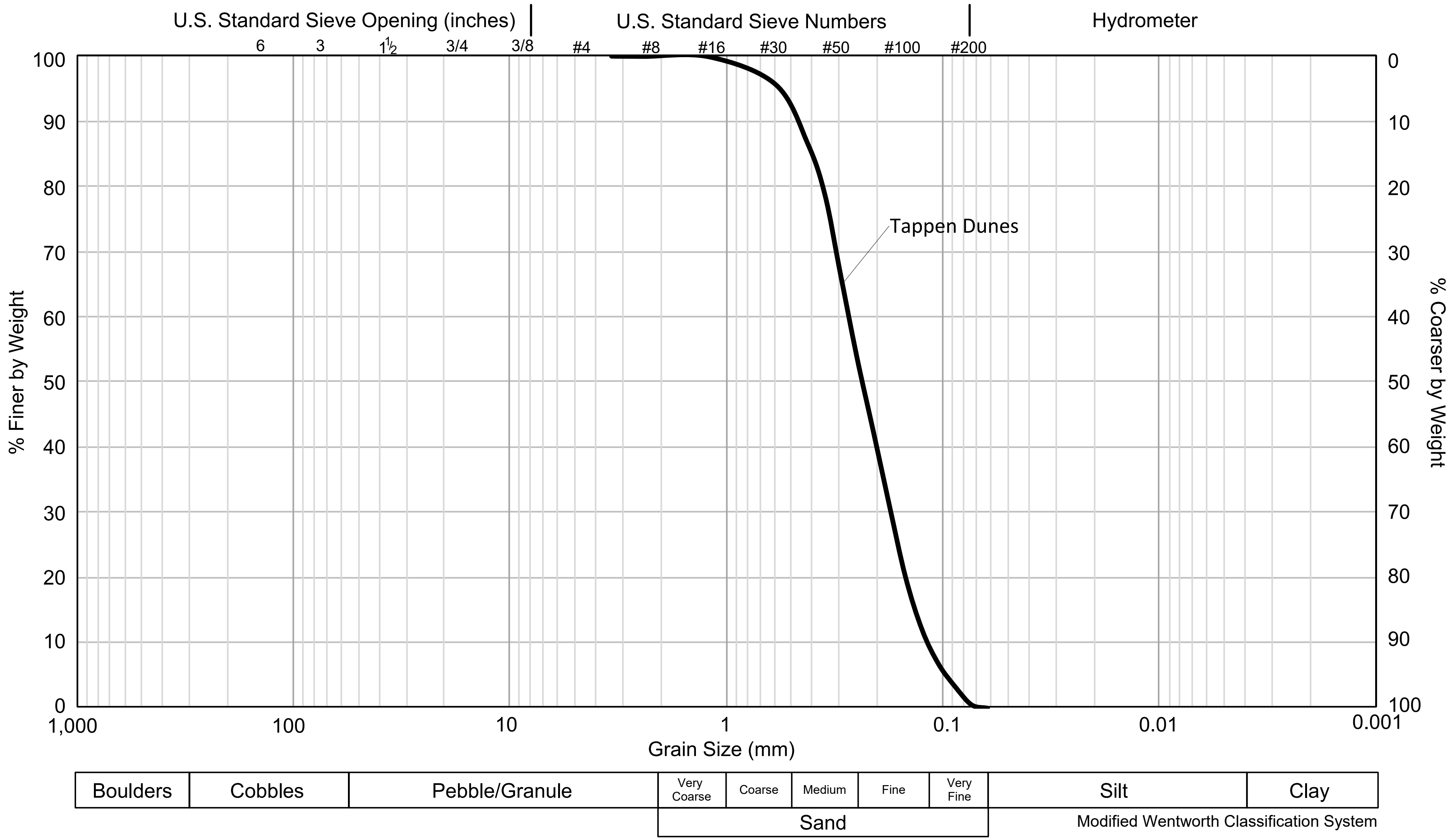


Figure A-I-14. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. 14 from the Tappen Dunes.

Appendix II. X-ray diffraction (XRD) Analysis of Windblown Sand Deposits in South-Central North Dakota

Introduction

Sampling of windblown sand from dune deposits in south-central, North Dakota was completed in 2020 as a part of an ongoing investigation into the utilization of North Dakota sand sources for use as natural sand proppant for the hydraulic fracturing of oil and gas wells in the Williston Basin. A total of 14 samples from 11 locations were collected from low and high-relief dune fields across southern Burleigh, southern Kidder, and northern and western Emmons County. Samples were submitted to Lonquist Frac Sand Services in Austin, Texas for proppant testing and X-ray diffraction (XRD) mineralogical analysis.

XRD-Methodology

The analytical patterns shown in the phase diagrams of Figures A-II-1 through A-II-14 included in this appendix represent the identified mineralogical phases contained within each sample. The identified phases were further quantified with the aid of a Rietveld refinement which more precisely defines the diffraction phase diagram peak heights and position which provides for greater accuracy in the mineralogic quantification. It should be noted that these sands were found to be essentially devoid of carbonate minerals in the washed sample size classes tested and during field testing with dilute (10%) HCl acid.

Figure A-II-1. XRD phase diagram of sample no. 1 from the Braddock Dunes in northeastern Emmons County, North Dakota.

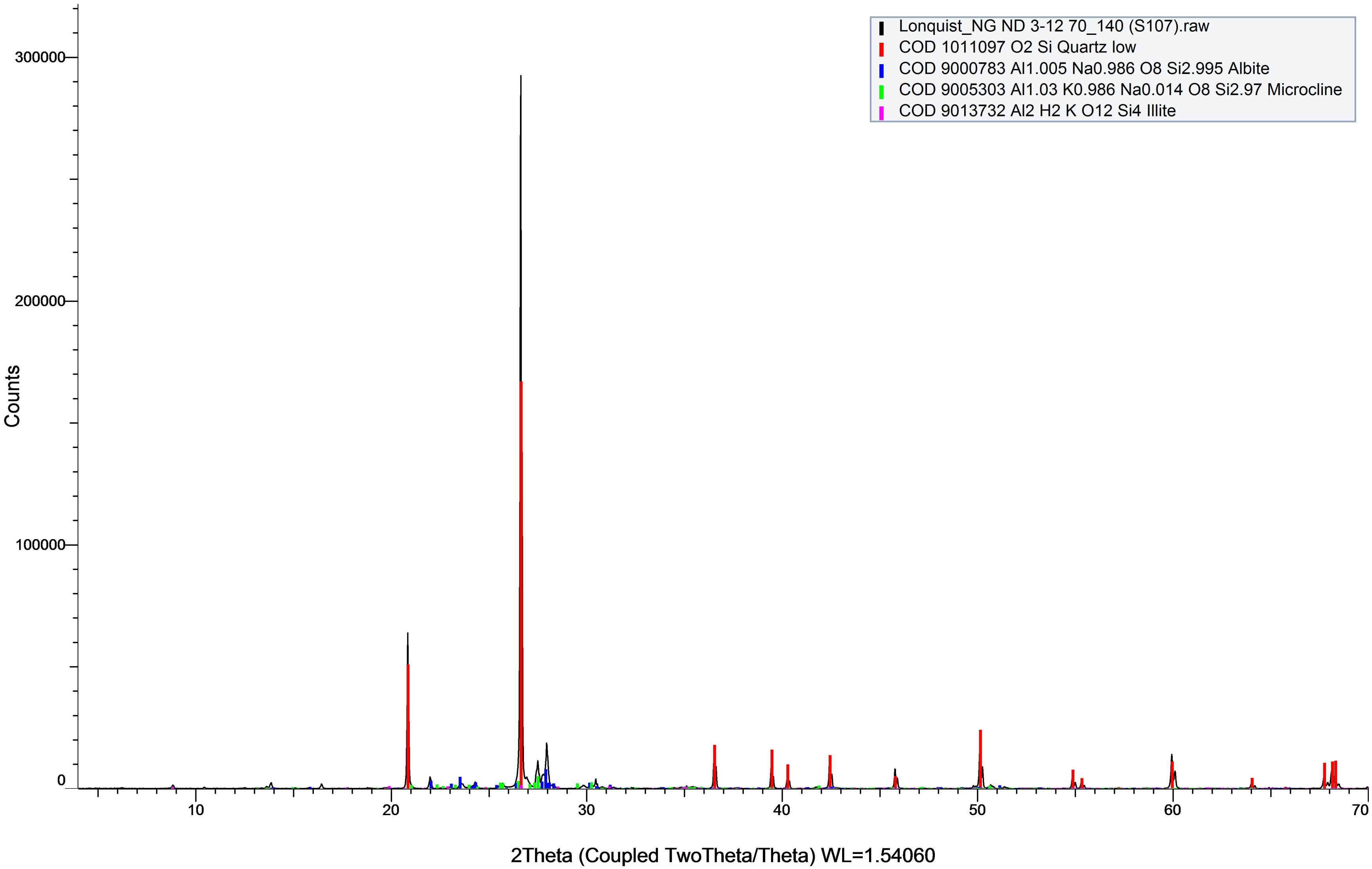


Figure A-II-2. XRD phase diagram of sample no. 2 from the Cat Tail Creek Dunes in southwestern Emmons County, North Dakota.

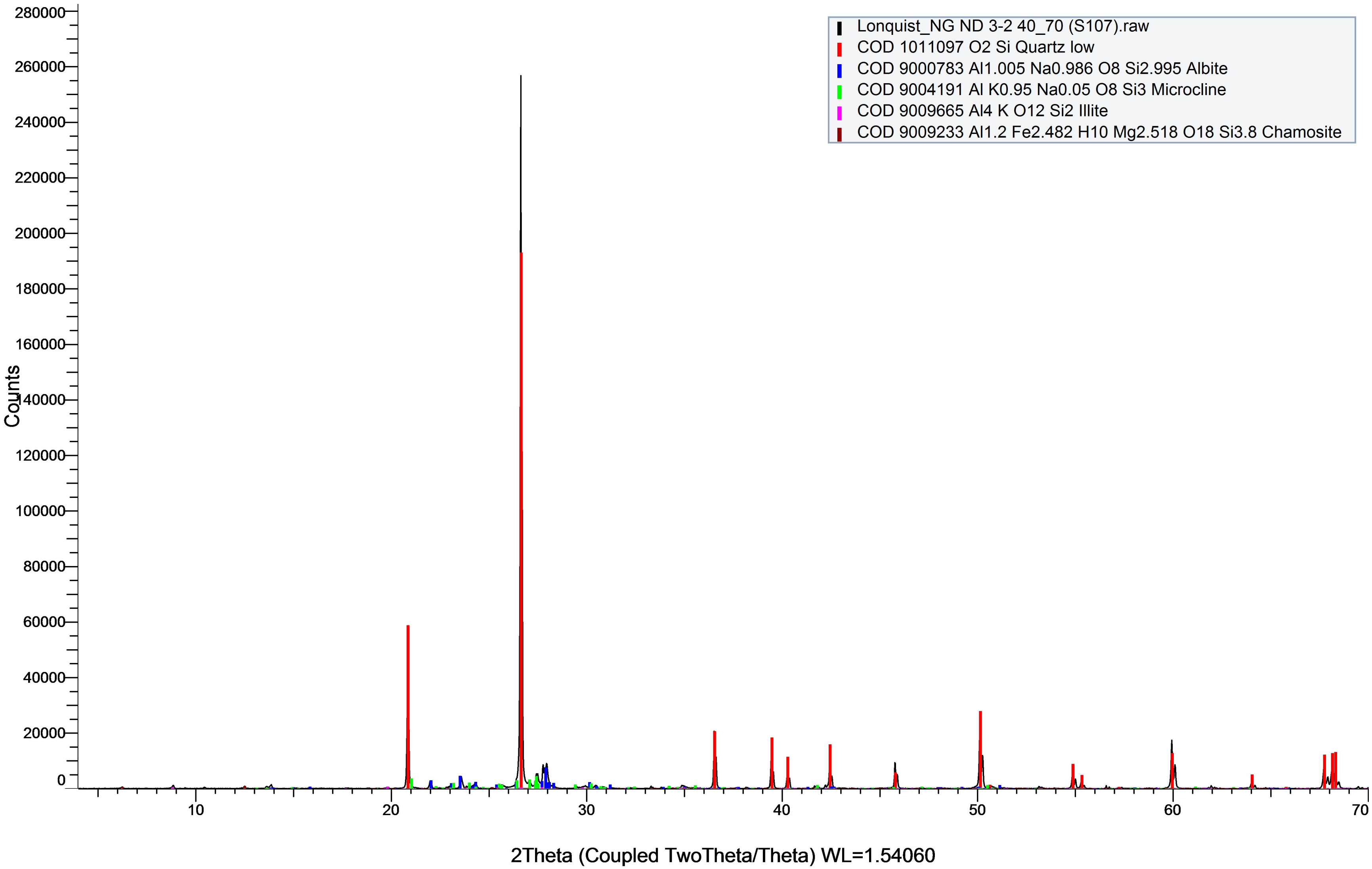


Figure A-II-3. XRD phase diagram of sample no. 3 from the Dana Dunes in northern Emmons County, North Dakota.

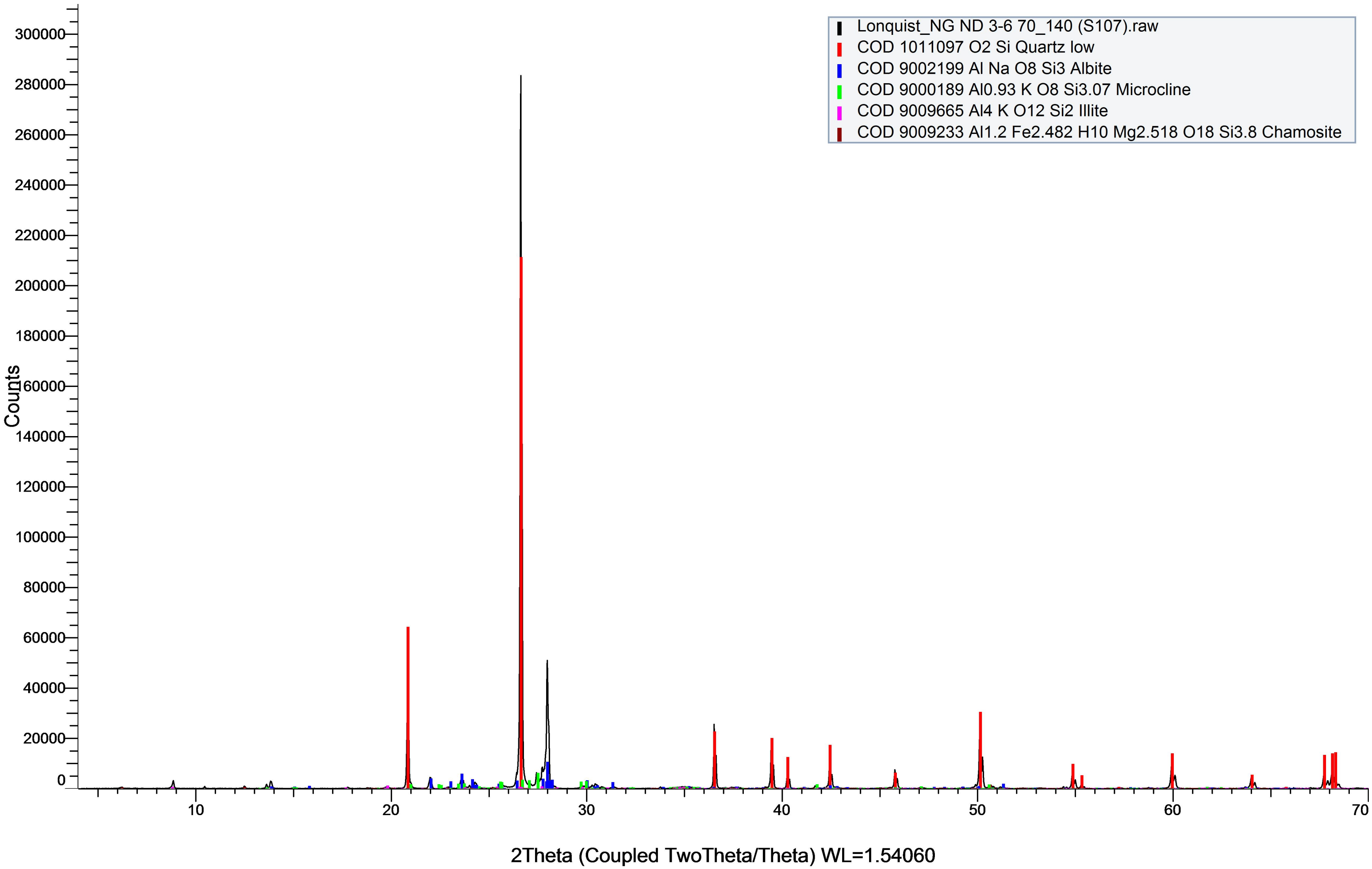


Figure A-II-4. XRD phase diagram of sample no. 4 from the Dawson Dunes in southern Kidder County, North Dakota.

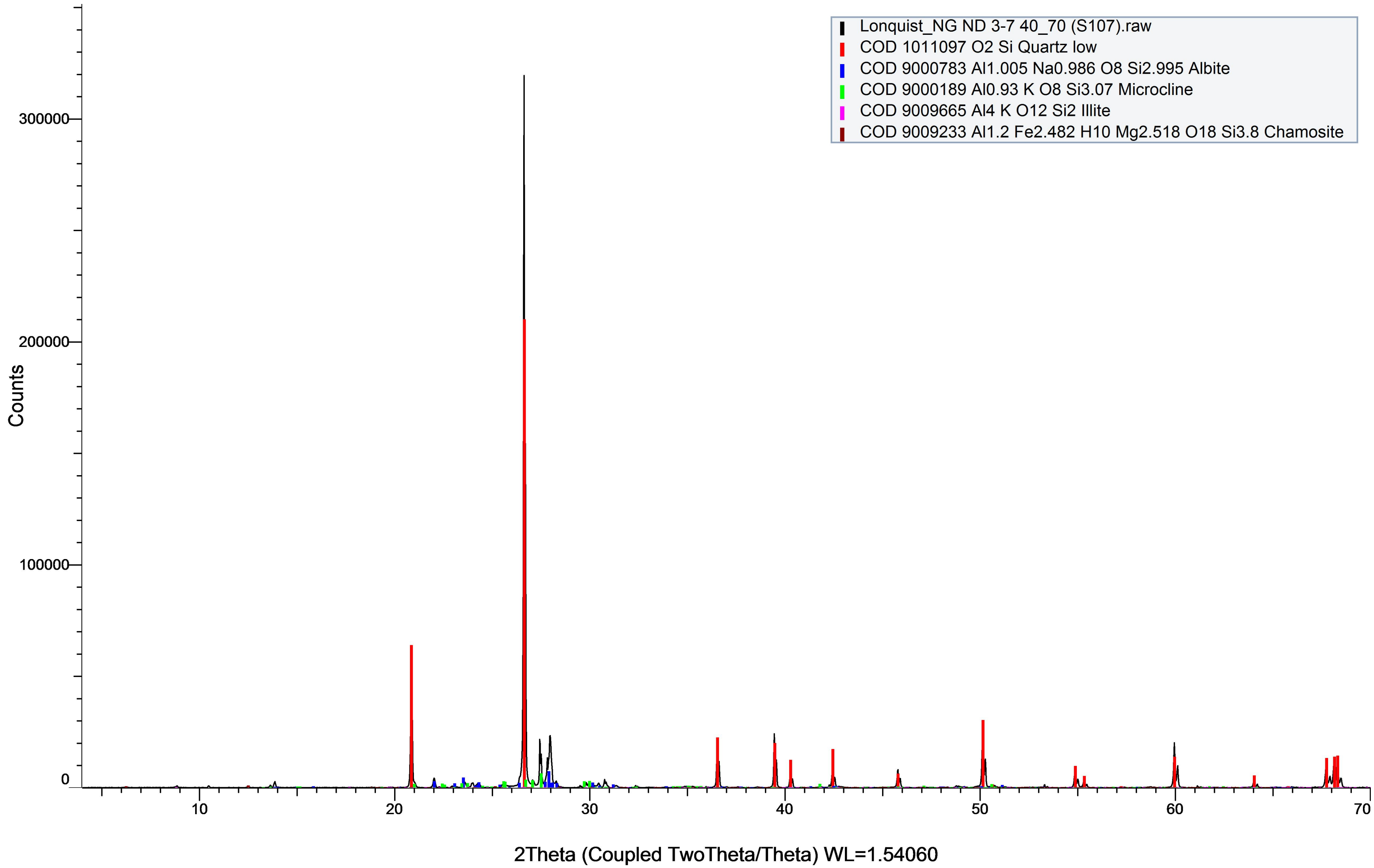


Figure A-II-5. XRD phase diagram of sample no. 5 from the Glencoe Creek Dunes in southern Burleigh County, North Dakota.

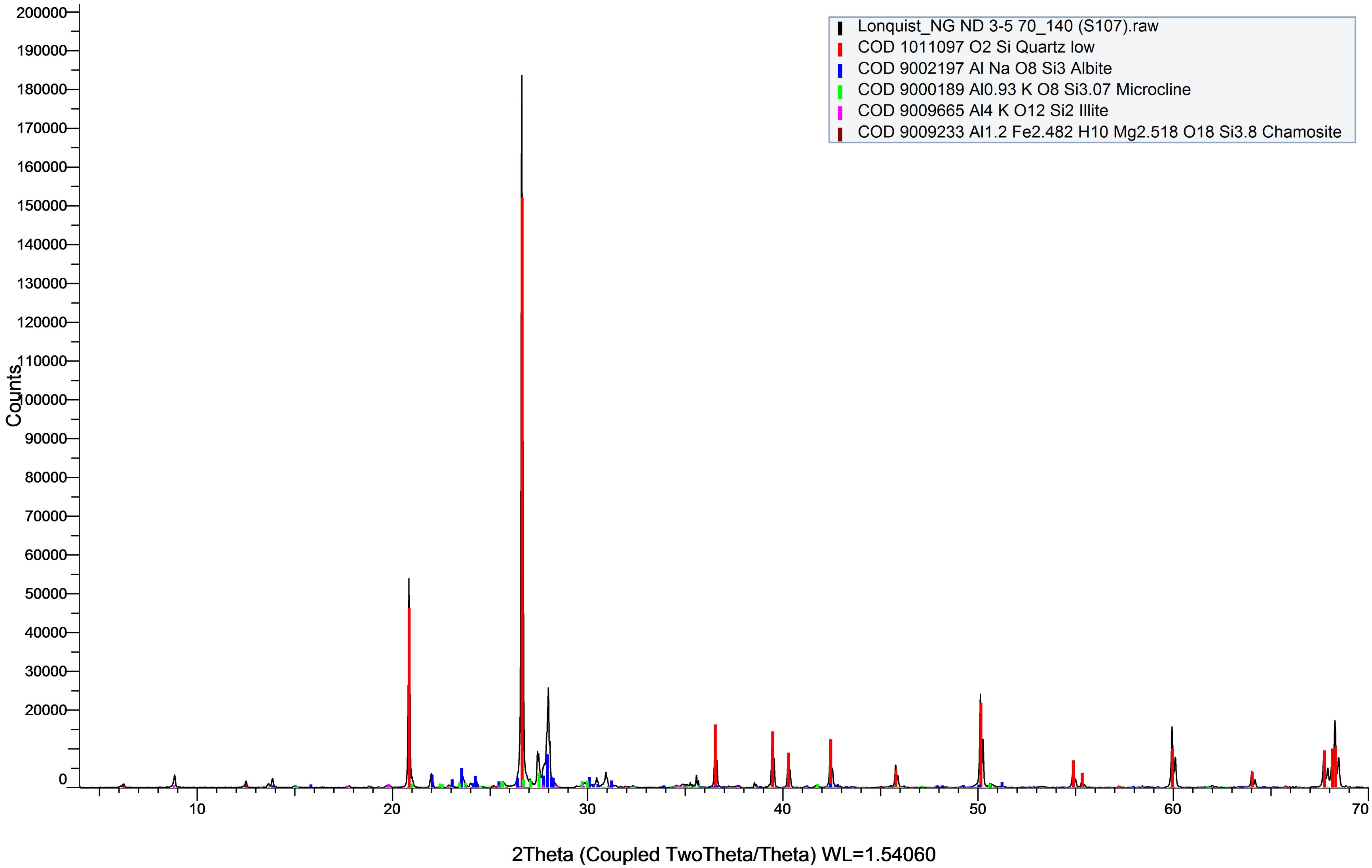


Figure A-II-6. XRD phase diagram of sample no. 6 from the Horsehead Valley Dunes in west-central Emmons County, North Dakota.

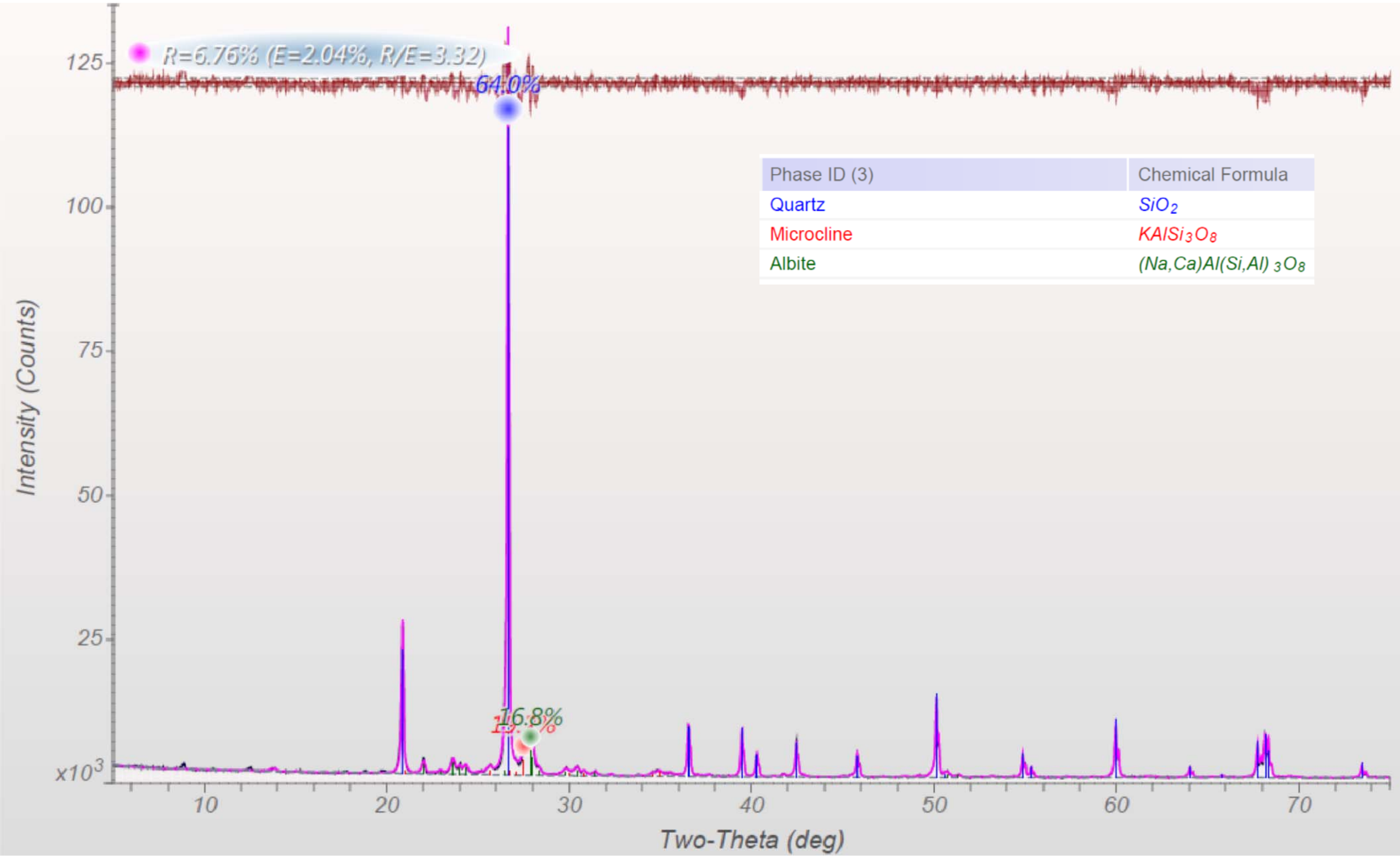


Figure A-II-7. XRD phase diagram of sample no. 7 from the Lincoln Dunes (LD-1) in southwestern Burleigh County, North Dakota.

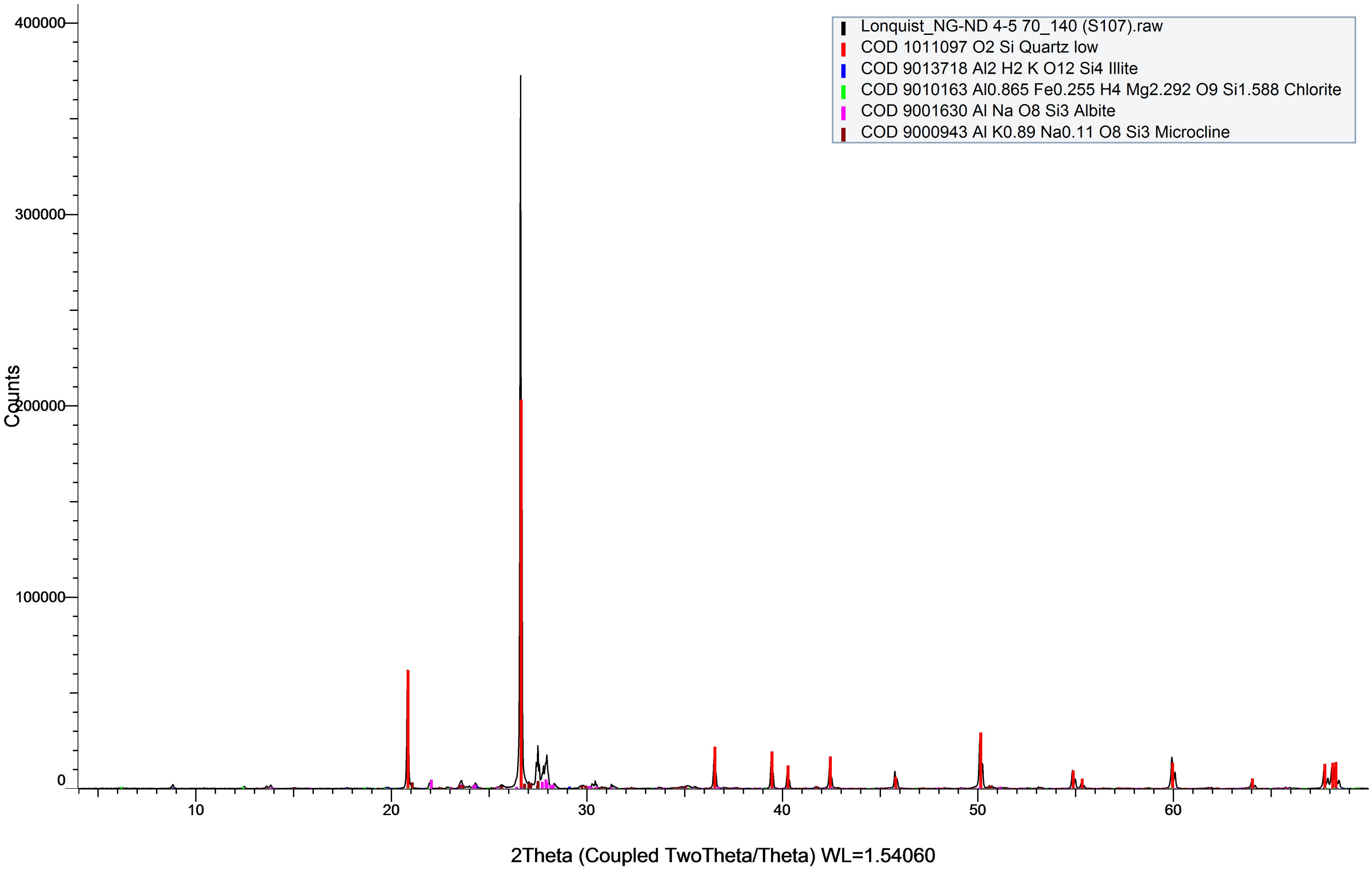


Figure A-II-8. XRD phase diagram of sample no. 8 from the Lincoln Dunes (LD-2))in southwestern Burleigh County, North Dakota.

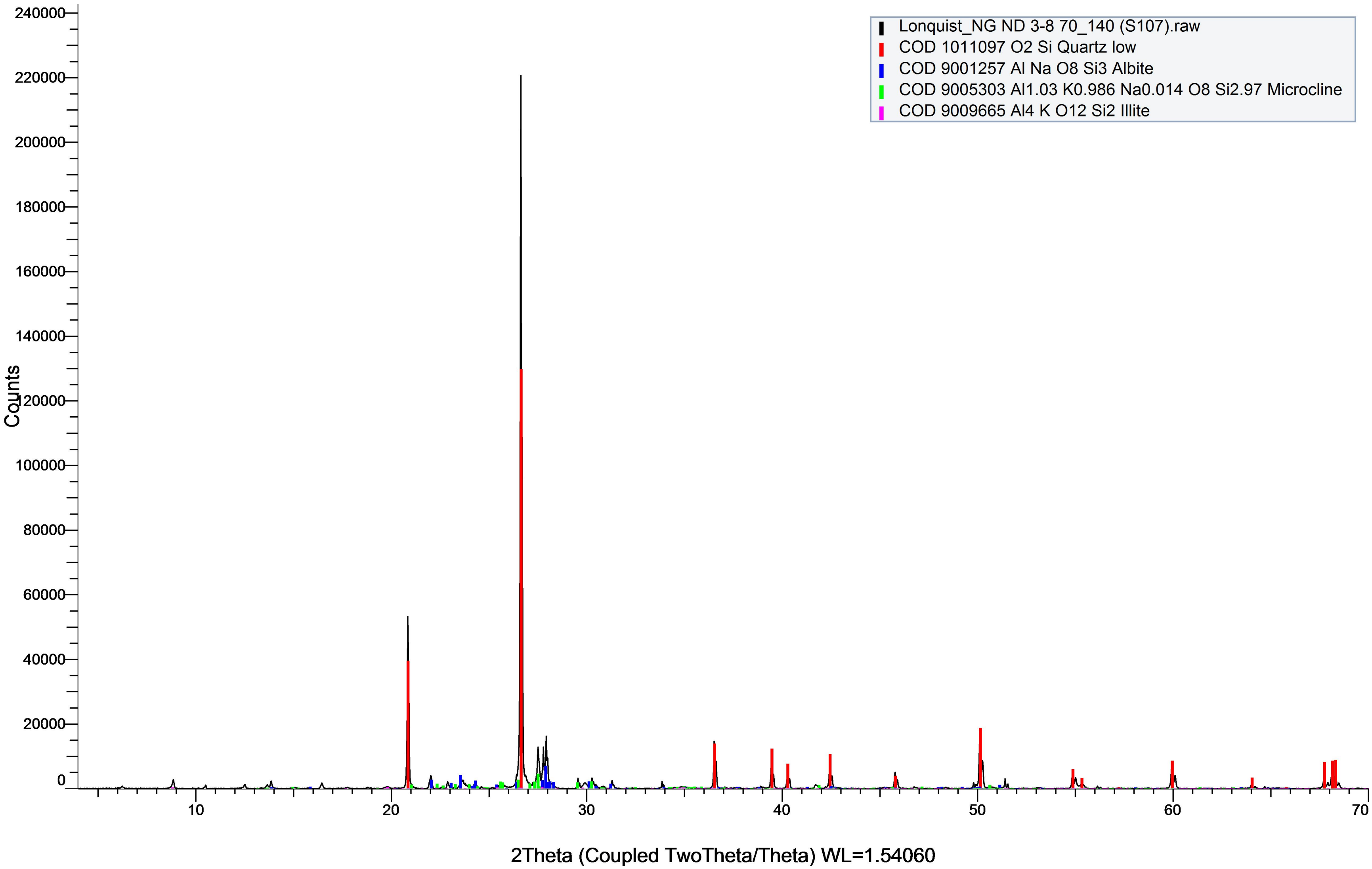


Figure A-II-9. XRD phase diagram of sample no. 9 from the Lincoln Dunes (LD-3u) in southwestern Burleigh County, North Dakota.

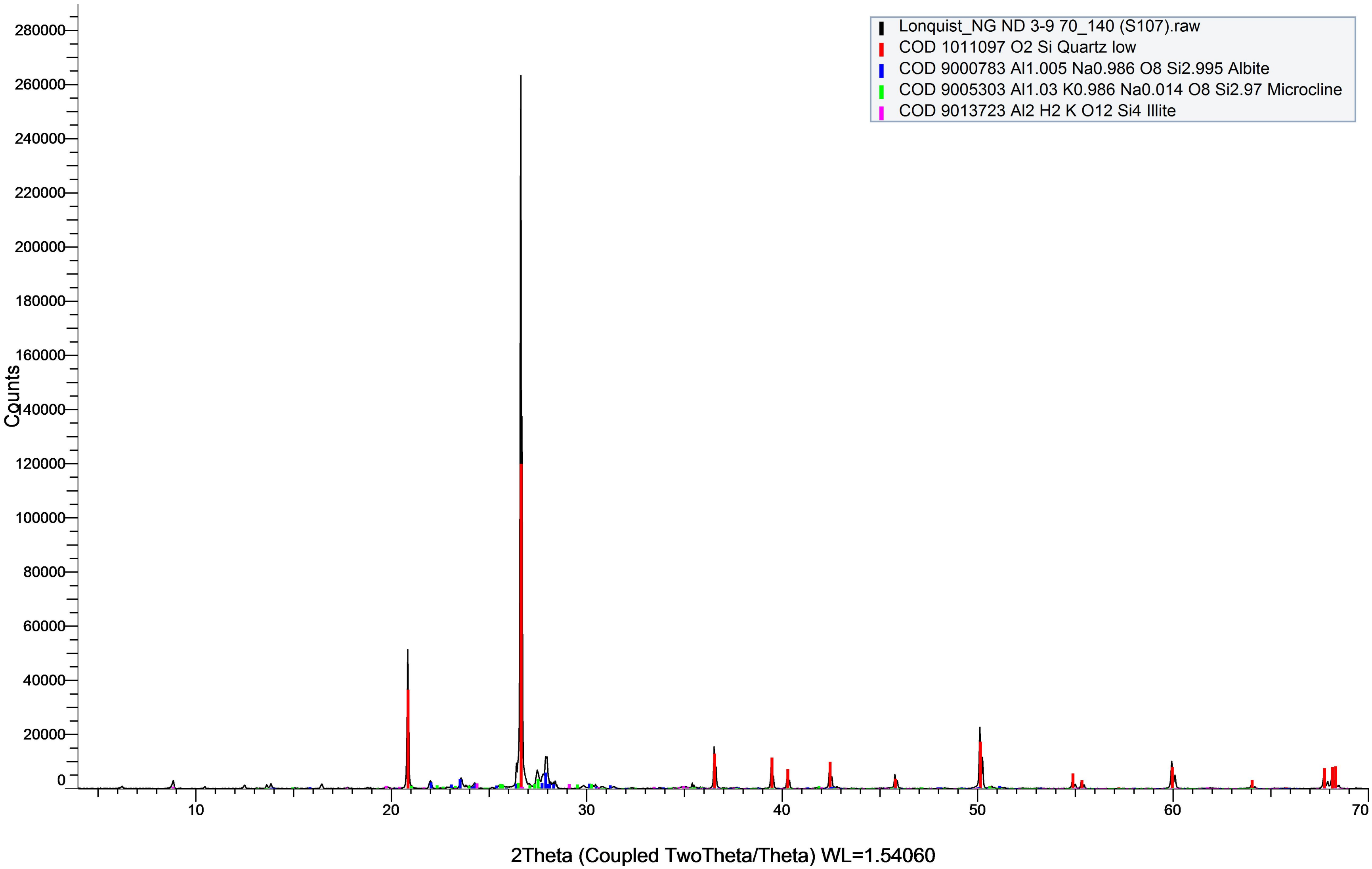


Figure A-II-10. XRD phase diagram of sample no. 10 from the Lincoln Dunes (LD-4l))in southwestern Burleigh County, North Dakota.

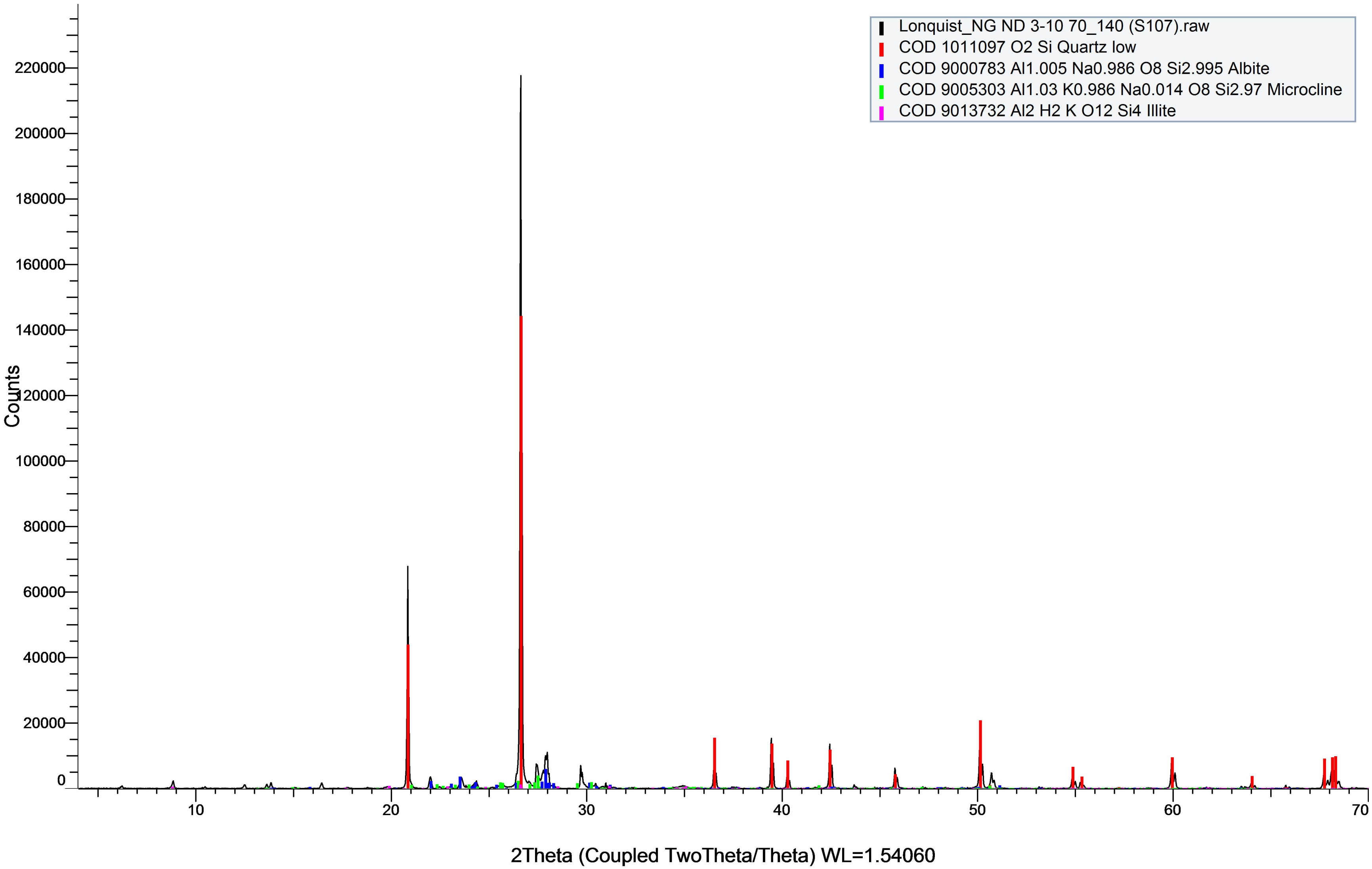


Figure A-II-11. XRD phase diagram of sample no. 11 from the Linton Dunes in southcentral Emmons County, North Dakota.

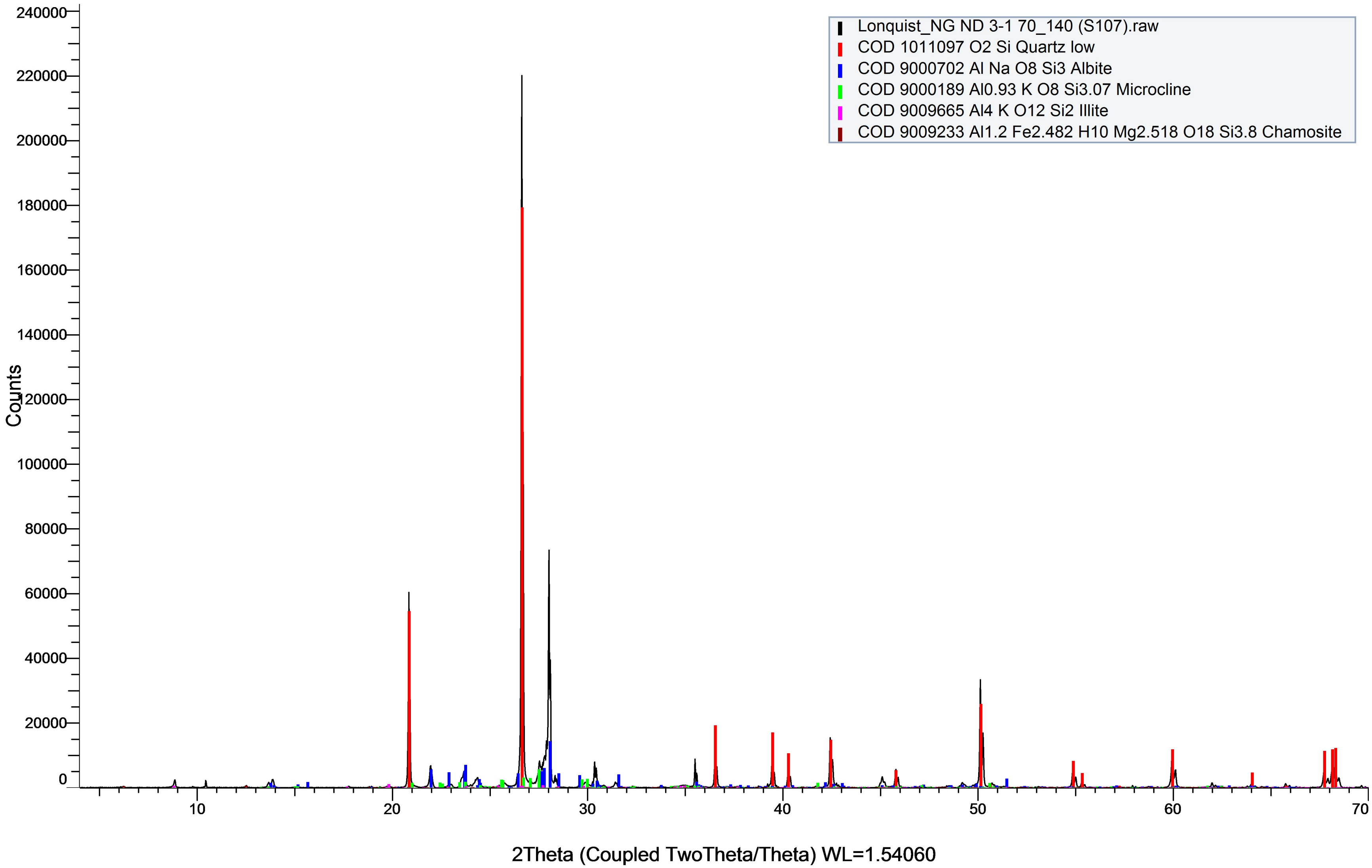


Figure A-II-12. XRD phase diagram of sample no. 12 from the McKenzie Dunes in southern Burleigh County, North Dakota.

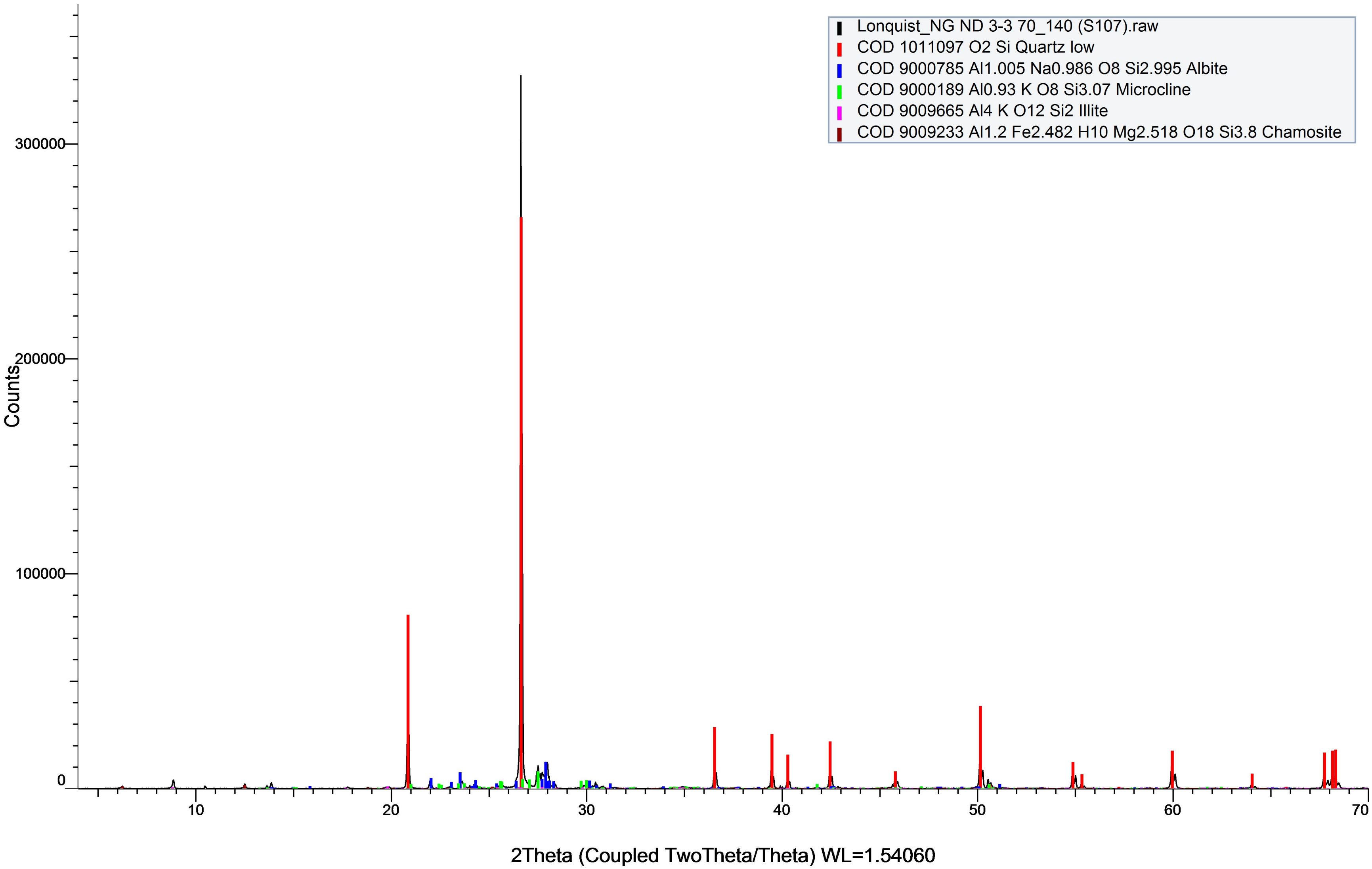


Figure A-II-13. XRD phase diagram of sample no. 13 from the Southwest Burleigh County Dunes, North Dakota.

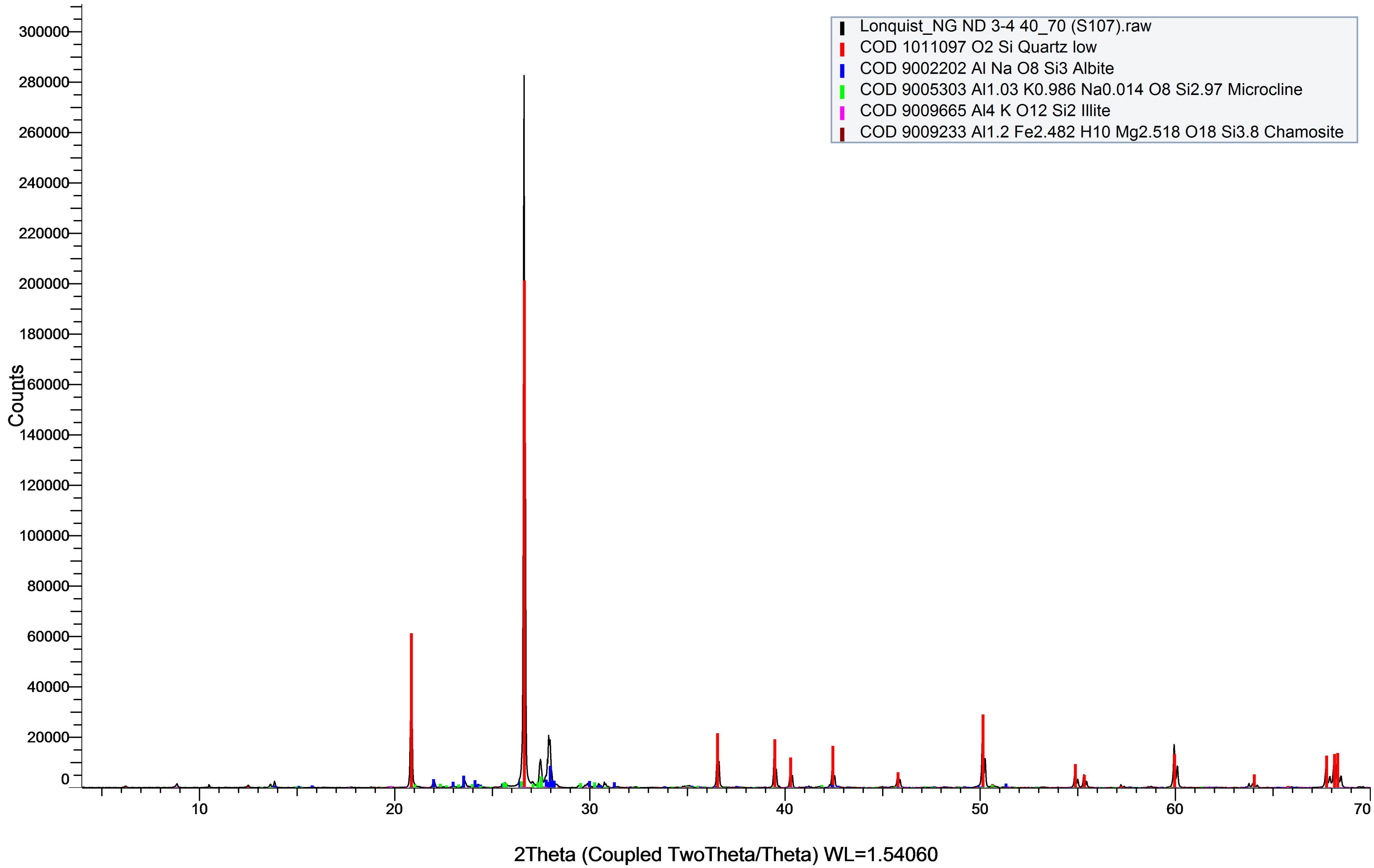
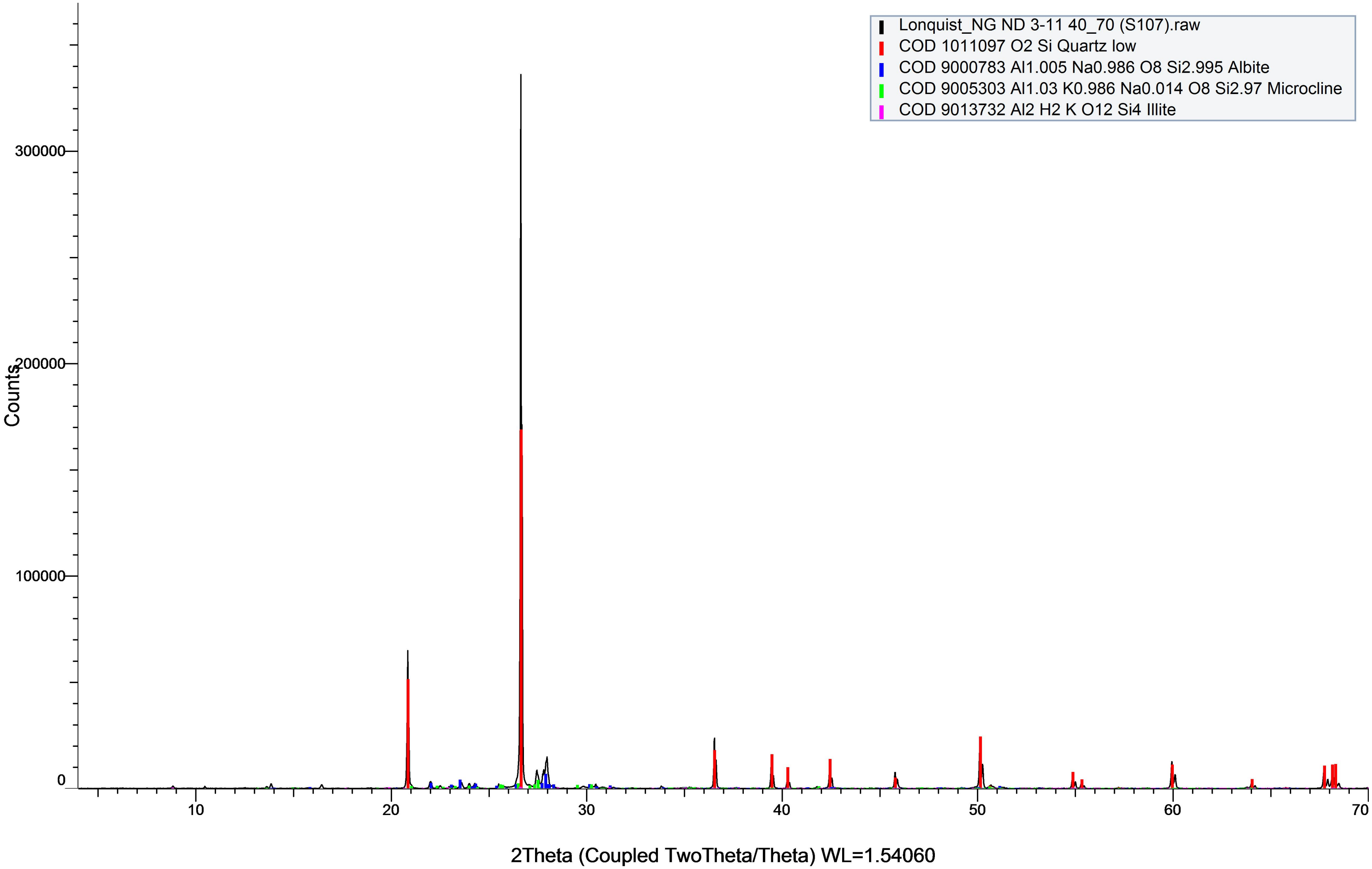


Figure A-II-14. XRD phase diagram of sample no. 14 from the Tappen Dunes in southern Kidder County, North Dakota.



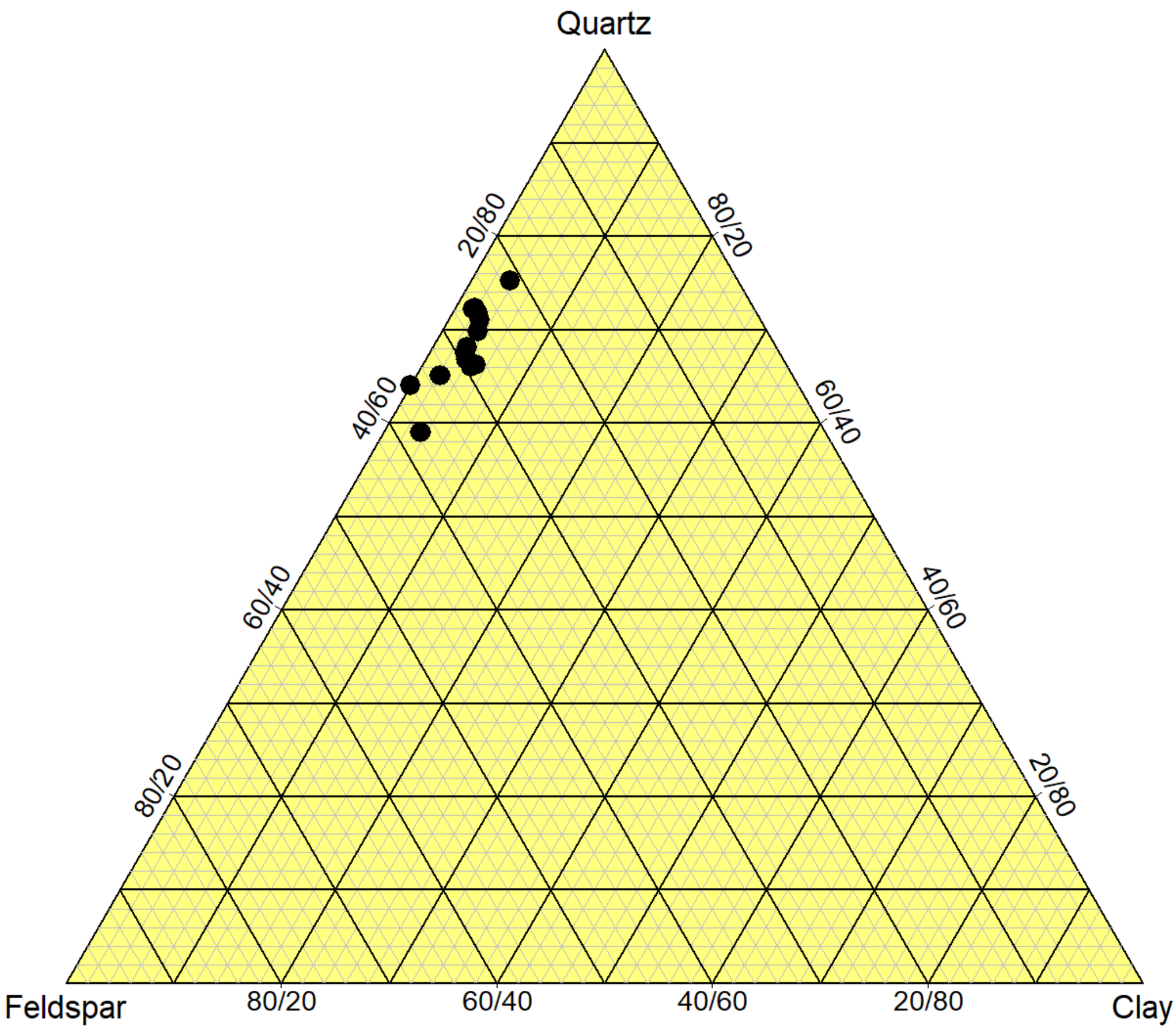


Figure A-II-15. Ternary diagram of processed (washed and sized) sand mineralogy (weight %) from X-ray diffraction (XRD) analysis of windblown sand deposits in south-central North Dakota. These sands tend to be quartz dominated with moderate amounts of feldspars and little clays. The close grouping in this graph illustrates how similar the mineralogy of these deposits are to one another.

Appendix III. Mineralogy of Bulk Windblown Sand Deposits in South-Central North Dakota by X-ray diffraction (XRD) Analysis.

Introduction

XRD analysis of bulk (unwashed and unsized) windblown sand from selected dune deposits in south-central North Dakota was completed in 2020 as a supplemental mineralogical investigation supporting the utilization of North Dakota sand sources for use as natural sand proppant for the hydraulic fracturing of oil and gas wells in the Williston Basin. A total of 11 samples were collected from 8 dune fields in southern Burleigh, southern Kidder, and northern and western Emmons County. Samples were submitted to Stim-Lab, Inc. in Duncan, Oklahoma for analysis.

XRD Methodology

The testing values reported in Table A-III-1 included in this appendix represent the identified mineralogical phases contained within each sample as reported in weight %. It should be noted that these sands were also found to be essentially devoid of carbonate minerals consistent with field tests with dilute (10%) HCl acid performed during sample collection.

Table A-III-1. Bulk Sand X-ray diffraction (XRD) Mineralogy Analytical Summary (Weight %)

Dune Deposit	Quartz	Feldspars (%)			Carbonates (%)			Clays (%)					Other Minerals (%)			
		Plagioclase	K-Feldspar	Feldspars*	Calcite	Dolomite	Carbonates*	Illite	Illite/Smectite	Chlorite	Kaolinite	Clays*	Micas	Hornblende	Pyrite	Iron Oxides
Braddock	60	17	8	25	--	--	--	3	1	*tr.*	1	5	10	--	--	--
Dana	69	11	8	19	--	--	--	3	3	*tr.*	2	8	4	--	--	--
Dawson	70	13	11	24	--	--	--	2	1	*tr.*	1	4	2	--	--	--
Horsehead Valley	65	12	12	24	--	--	--	3	2	*tr.*	1	6	5	--	--	--
Lincoln (LD-1)	72	11	8	19	--	--	--	2	2	*tr.*	1	5	4	--	--	--
Lincoln (LD-2)	71	11	7	18	--	--	--	2	1	1	2	6	5	--	--	--
Lincoln (LD-3u)	66	12	11	23	--	--	--	1	1	*tr.*	4	6	5	--	--	--
Lincoln (LD-4l)	70	12	7	19	--	--	--	2	1	1	2	6	5	--	--	--
Linton	64	14	8	22	--	--	--	5	2	*tr.*	2	9	5	--	--	--
McKenzie	66	10	9	19	--	--	--	4	2	1	3	10	5	--	--	--
Tappen	70	12	11	23	--	--	--	1	1	*tr.*	*tr.*	2	5	--	--	--

* *Undifferentiated*

-- *Mineral not detected*

tr. trace

APPENDIX IV. 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 sample's 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. Sand with a high quartz content is desirable.