Evaluation of Windblown Sand Deposits in Eastern North Dakota for Potential Use as Proppant

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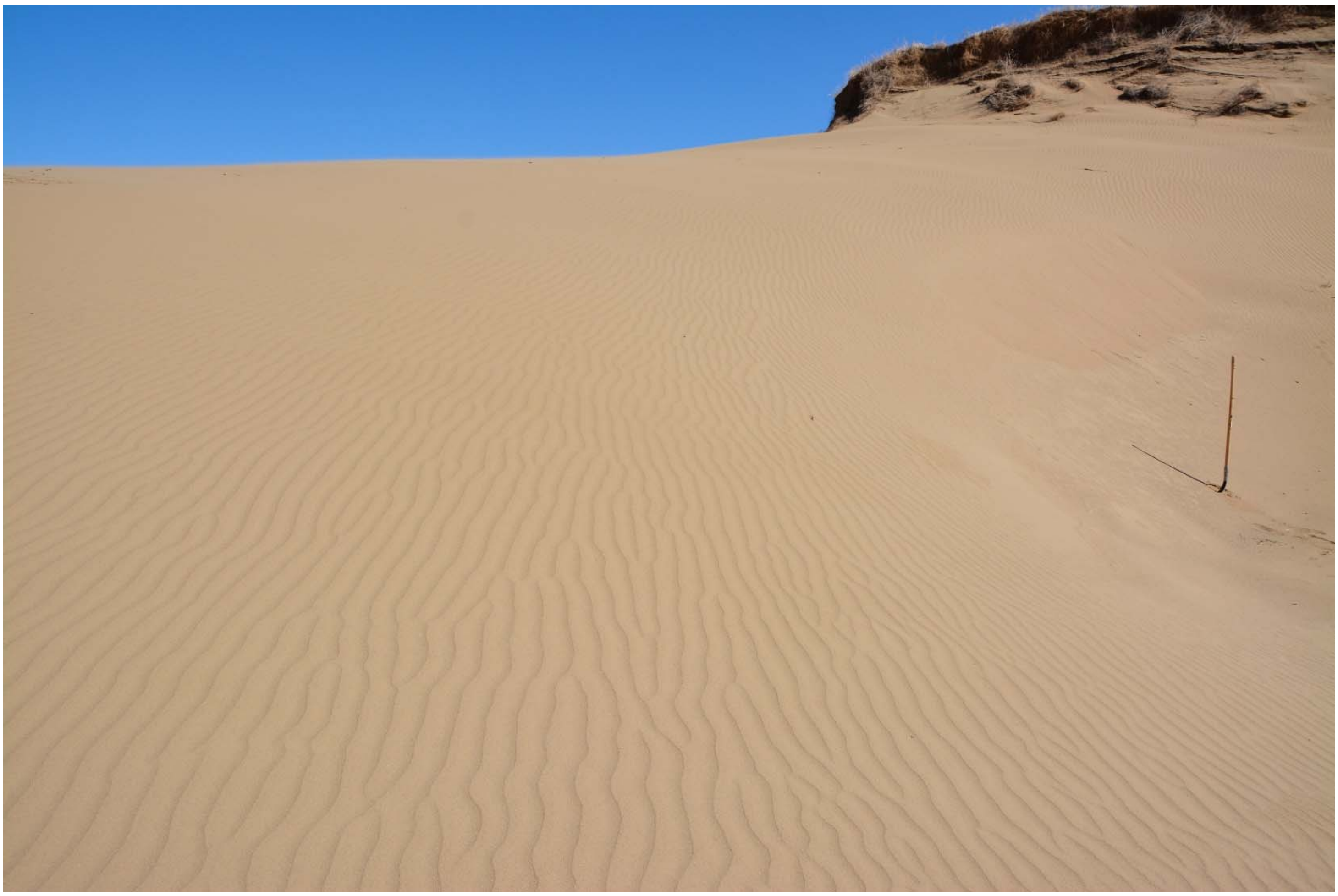

REPORT OF INVESTIGATION NO. 127
NORTH DAKOTA GEOLOGICAL SURVEY
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Abstract

Sampling and testing of windblown sand deposits in eastern North Dakota was completed in late 2020 and early 2021. Sand samples were collected 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 11 samples from seven areas of windblown sand in northeastern and southeastern North Dakota. These windblown sand deposits are found in localized low-relief (<10-ft) and high-relief (>10-ft) dune fields and as wind-scoured sheet sands of limited thickness and cover approximately 1,194 square miles (3,092 km^2) or 764,160 acres. Selected sand size classes (40/70, 70/140 and 40/140) were tested as these represented the most abundant grain sizes which are consistently well sorted, medium to very-fine grained, with crush resistance of 5,000 psi (5K) in the 40/70, 70/140, and 40/140 size classes and 7,000 psi (7K) and 9,000 psi (9K) in the 40/140 size classes from the Brampton and Pembina Dunes, respectively. Acid solubility averaged 7.4% and turbidity 32.1% with very low loss on ignition (LOI) values averaging 0.4%, suggesting a low presence of detrital lignite and deleterious mineralogy. Sand grain particle shape factors approach the desired ranges for proppant use and average 0.8 for roundness and 0.5 for sphericity. Mineralogically, no carbonates were found in the washed and sized samples which averaged 68% quartz, 30% felspar (albite and microcline), and 2.3% clay (illite). 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 Hazen-Stanton and Denbigh Dunes where proppant sand is currently being mined.

Acknowledgements

The authors would like to thank the various private landowners who provided access to the sampling areas contained in this report. Sand testing services (proppant analysis) was provided by Lonquist & Co., LLC in College Station, Texas. Cartographic support was provided by Mr. Navin Thapa, GIS Specialist with the North Dakota Geological Survey.

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 most prominent windblown sands that are found in eastern North Dakota, expanding the view of the possibilities for continued development of proppant sand resources across the state.

Cover photo: Sand ripples on a high-relief dune in the Brampton (Riverdale Ridge) Dunes in southwestern Sargent County. The dunes in this area can be as high as 30 feet (9.1 m).

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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 evaluate all of their exploration, completion and production costs. 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 (Anderson, 2011). 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 initially took place throughout the state (Anderson, 2011) and then focused on western North Dakota (Anderson, 2018, 2019 a&b, 2020 a-c). More recently, sampling was concentrated in the larger dune fields in northeastern and southeastern North Dakota in an effort to identify additional proppant sand sources that could support future oil development activity in the Williston Basin.

Eleven sand samples from seven windblown sand deposits were collected during the 2020 and 2021 field seasons and submitted to Lonquist & Co., LLC's frac sand testing lab in College Station, Texas, for proppant characterization (Figure 1). Bulk sand samples were collected in five-gallon buckets at selected windblow sand locations (Sample Nos. 1 – 11) distributed across eastern North Dakota (Figure 1). Samples were collected from within areas of low-relief (<10 feet) sand dunes, wind-scoured sheet sands of limited thickness, and high-relief (>10 feet) dunes in larger coalesced dune fields (Table 1). Dune samples were collected beneath the vegetative cover and weathered surface horizons (generally three to five feet below land surface) using traditional pioneer 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) and the International Organization for Standardization (ISO) (API, 2018, and 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 70/140 size classes. Samples where testing was completed on more than one size cut are labeled as a and b. For example, Sample Nos. 4a and 4b, which are the 40/70 and 40/140 size cuts from the same sample collected at location 4.

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, but over time this 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. Also broadening the testing size class range, such as in a 40/140 or 50/140, cut has resulted in higher crush resistance values in some samples.

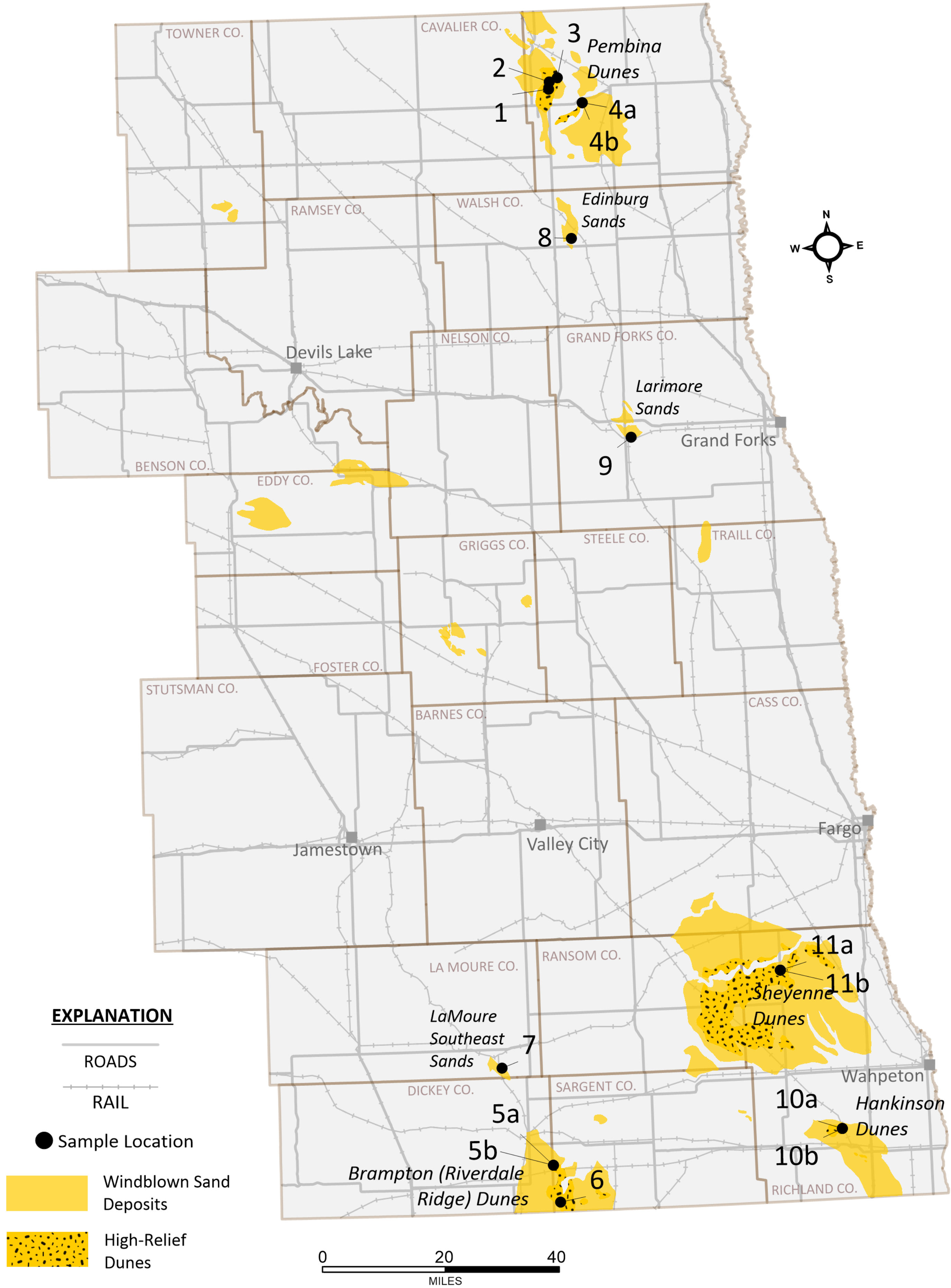

Figure 1. The windblown sand deposits of eastern North Dakota.

Table 1. Windblown Sand Sample Location Summary

Sample No.	Windblown Sand Area	County	Location (PLSS)	Description	Testing Completed	Field Acid Reactivity (10% HCl)
					API 19C Proppant (wXRD)	
1	Pembina Dunes (PD-2)	Pembina	161-56-2-NW	High Dunes, Ground Exposure	X	NR
2	Pembina Dunes (PD-3)	Pembina	162-56-26-SW	High Dunes, Ground Exposure	X	NR
3	Pembina Dunes (PD-4)	Pembina	162-56-25-NE	High Dunes, Ground Exposure	X	NR
4	Pembina Dunes (PD-5)	Pembina	161-55-15-SE	High Dunes, Dune Face Exposure	X	NR
5	Brampton Dunes North	Sargent	130-58-19-SW	High Dunes, Dune Face Exposure	X	NR
6	Brampton Dunes South	Sargent	129-58-29-NW	High Dunes, Dune Face Exposure	X	NR
7	LaMoure Southeast	LaMoure	133-60-25-NW	Sheet Sands, Ground Exposure	X	NR
8	Edinburg Sands	Walsh	157-55-18-SW	Sheet Sands, Ground Exposure	X	NR
9	Larimore Sands	Larimore	151-54-8-SW	Sheet Sands, Ground Exposure	X	NR
10	Hankinson Dunes	Richland	131-50-34-SE	High Dunes, Dune Face Exposure	X	NR
11	Sheyenne Dunes	Richland	135-51-7-NE	High Dunes, Dune Face Exposure	X	NR

NR = Non-Reactive.

PREVIOUS WORK

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 deposits 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 predominantly within McHenry County in 2019. Extensive proppant sand testing and characterization work was performed across the Denbigh Windblown Sands area (Anderson, 2020b) which concluded that these deposits are 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, 2020c).

In 2020 the Geological Survey continued sampling and testing work on dune deposits in south-central North Dakota in southern Burleigh and Kidder, as well as northern and western Emmons Counties, and found these deposits to be of marginal character with respect to use as proppant (Anderson, 2020a). These deposits were determined to be slightly lower in quality to windblown sand deposits found in Mercer and McHenry Counties.

WINDBLOWN SAND IN EASTERN NORTH DAKOTA

Areas of windblown sand in eastern North Dakota are found primarily in the northeastern and southeastern parts of the state (Figure 1). Appreciable deposits are found in Pembina, Richland, Dickey and Sargent Counties (Clayton, et al, 1980). Several smaller more localized areas of windblown sand that are included in this study are found in Walsh, Grand Forks, and LaMoure Counties. Additional smaller areas, not included in this study, can be found in Towner, Eddy, Griggs, and Trail Counties. The most prominent windblown sand areas contain significant dune fields and include the Pembina, Sheyenne, and Brampton (Riverdale Ridge) Dunes. These areas contain coalesced high-relief dunes generally greater than 10 ft (3m) in height and can reach heights of up to 30 feet (10m) or more (Table 1). These sand deposits originate from reworking of deltaic sediments deposited in the former Glacial Lake Agassiz, local glacial outwash plains, and regional proglacial lacustrine deposits. 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 the areas included in this investigation cover approximately 1,194 square miles (3,092 km^2) or 764,160 acres. Previous workers have delineated windblown sand in North Dakota into high and low-relief dune settings as this has been the common geologic mapping convention (e.g., Clayton et. al., 1980). The use of this descriptive terminology is continued here.

Sand Deposits in High-Relief Dune Fields

There are four windblown sand areas that contain high-relief dunes and include (from largest to smallest areal extent): the Sheyenne, Pembina, Brampton (Riverdale Ridge), and Hankinson Dunes. These areas cover an estimated 1,158 square miles (2,999 km^2) or 741,120 acres. The high-relief dune fields tend to be concentrated in the central portions of these mapped windblown sands (Plates I & II), Dune forms tend be in line with prominent paleo-wind directions which are predominantly from the northwest to the southeast. Eight of the 11 samples collected as a part of this investigation, were from high-relief dune settings (Table 1).

Low-Relief Dunes and Sheet Sands

The other three windblown sand areas: the LaMoure Southeast, Edinburg, and Larimore Sands contain gently rolling to flat tabular sheet sands with occasional low-relief dunes and are of limited extent and thickness. These areas cover approximately 36 square miles (93 km^2) or 23,040 acres. Three of the 11 samples, one in each area, were collected for this investigation (Table 1). Some six additional windblown sand areas of limited extent (not included in this investigation) can be found in east-central North Dakota (Figure 1). It is presumed that sand quality and character in these smaller areas would be similar to what has been found in south-central North Dakota (Anderson, 2021a) and to what is included here for Sample Nos. 7 – 9.

SAND SAMPLE LOCATIONS

Bulk samples of windblown sand were collected in five-gallon buckets from prominent dune field and sheet-sand deposits in eastern North Dakota in September 2020 and from March to May 2021. Each of the eleven samples collected were submitted to Lonquist & Co. LLC for proppant (frac sand) testing (Fig. 1). 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.

Samples No. 1 – 4 - Pembina Dunes

Sample Nos. 1 - 4 were collected from hand-shovel pits excavated in high-relief dunes in northwestern Pembina County (Figure 1, Table 1). Samples 1-3 were collected from the northern Pembina Dunes within the footprint of the Jay V. Wessels Wildlife Management Area currently managed by the North Dakota Game and Fish Department. Sample No. 4 was collected in the northern portion of the southern Pembina Dunes (Figure 1) located 1.5 miles (2.4 km) south of Akra.

Sample No. 5 – Brampton (Riverdale Ridge) Dunes

Sample No. 5 was collected from a hand-shovel pit excavated into a westward facing high-relief dune exposure in the northern Brampton (Riverdale Ridge) Dunes in southwestern Sargent County (Figures 1 and 3, Table 1). This sample location is located approximately seven miles southeast of Oakes and 8.2 miles north of the South Dakota border.

Sample No. 6 – Brampton (Riverdale Ridge) Dunes

Sample No. 6 was collected from a hand-shovel pit excavated into a southward facing high-relief dune exposure in the southern Brampton (Riverdale Ridge) Dunes in southwestern Sargent County (Figures 1 and 4, Table 1). This sample location is located approximately 13 miles southeast of Oakes and 1.6 miles north of the South Dakota border.

Sample No. 7 – LaMoure County Southeast Windblown Sands

Sample No. 7 was collected from a hand-shovel pit on a ground exposure in the central portion of the LaMoure County Southeast Windblown Sands in southeastern LaMoure County (Figure 1, Table 1). This sample location is located 6.5 miles southeast of Lamoure and 6.5 miles southwest of Verona.

Sample No. 8 – Edinburg Sands

Sample No. 8 was collected from a hand-shovel pit excavated into a low-relief dune exposure in the southern (presumably downwind) portion of the Edinburg Sands in north-central Walsh County (Figure 1, Table 1). This sample location is six miles southeast of Edinburg and two miles northwest of Park River.

Figure 2. View to the north of a surface exposure in a high-relief dune in the northern Pembina Dunes in northwestern Pembina County, North Dakota. These dunes are inactive and have a well established cover of vegetation. Sample Nos. 1 - 4 were collected from the Pembina Dunes.

Figure 3. View to the east of a high-relief dune in the northern Brampton (Riverdale-Ridge) Dunes in southwestern Sargent County, North Dakota. Sample No. 5 was collected at this location.

Figure 4. View to the northeast across high-relief dunes located three miles north of the South Dakota border in southwestern Sargent County. Sample No. 6 was collected from this location (T.129N., R.58W., Sec.29, NW1/4).

Sample No. 9 – Larimore Sands

Sample No. 9 was collected from a hand-shovel pit excavated into a vegetated ground exposure along a tree line on the southern (presumably upwind) end of windblown sand mapped northeast of Larimore in west-central Grand Forks County (Figure 1, Table 1). This sample location is located one-half mile east of Larimore.

Sample No. 10 – Hankinson Dunes

Sample No. 10 was collected from a hand-shovel pit excavated into a grass covered high-relief dune along the northeastern margin of the Hankinson Dunes in south-central Richland County (Figure 1, Table 1). This sample location is located four miles northwest of Hankinson and 3.5 miles southeast of Mantador.

Sample No. 11 – Sheyenne Dunes

Sample No. 11 was collected from a hand-shovel pit excavated into a high-relief dune exposure in the Sheyenne Dunes in northwestern Richland County (Figure 1, Table 1). This sample location is located approximately two miles south of the Sheyenne River and adjacent to and west of Richland Co. Road 18.

Figure 5. View to the south along the northeastern edge of a high-relief dune field in the northern Hankinson Dunes in south-central Richland County, North Dakota. These dunes are stabilized by vegetation with a well established cover of native grasses, trees, and shrubs. Sample No. 10 was collected from these dunes.

Figure 6. View to the north of high-relief dunes in the northern Sheyenne Dunes in northwestern Richland County, North Dakota. These high-relief dunes, found south of the Sheyenne River, are also stabilized by vegetation with a well established cover of native grasses, trees, and shrubs. The local relief on these dunes is greater than 50 feet (15.2 m). Sample No. 11 was collected from these dunes.

DESCRIPTON 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 & Co., LLC, located in College Station, Texas in June of 2021.

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 (Figure 7). 40/140 cuts were also tested from the Pembina, Sheyenne, Hankinson, and Brampton (Riverdale Ridge) Dunes to evaluate the effects of a larger grain-size range on test results (Table 3).

Particle Size Distribution – Textural (Sieve) Analysis

Sieve analyses were conducted 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 either as tabular data (Table 4) or in graphical form on a grain-size distribution diagram (Figure 8).

The resulting graph and grain-size curves depict the volume 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 8). 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 11 samples were classified as “sand” according to the Modified Wentworth classification scheme (Figure 8) and can be further characterized as well sorted (poorly graded) to very well sorted, medium to very-fine grained sands. The majority of grains in these samples are within the 40/70 or 70/140 or “100 mesh” sand size ranges (Table 5).

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	Pembina Dunes (PD-2)	4.4	1.1	2.6	8.1	91.9
2	Pembina Dunes (PD-3)	7.2	2.0	8.6	17.8	82.2
3	Pembina Dunes (PD-4)	4.6	3.1	2.7	10.4	89.6
4	Pembina Dunes (PD-5)	3.0	11.1	0.9	15.0	85.0
5	Brampton Dunes North	3.1	5.7	1.8	10.6	89.4
6	Brampton Dunes South	4.1	0.7	6.4	11.2	88.7
7	LaMoure Southeast	7.4	3.8	6.8	18.0	81.9
8	Edinburg Sands	22.5	6.4	4.1	33.0	67.0
9	Larimore Sands	39.8	2.1	5.4	47.3	52.7
10	Hankinson Dunes	7.3	0.1	5.3	12.7	87.4
11	Sheyenne Dunes	9.7	0.0	5.9	15.6	84.4

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

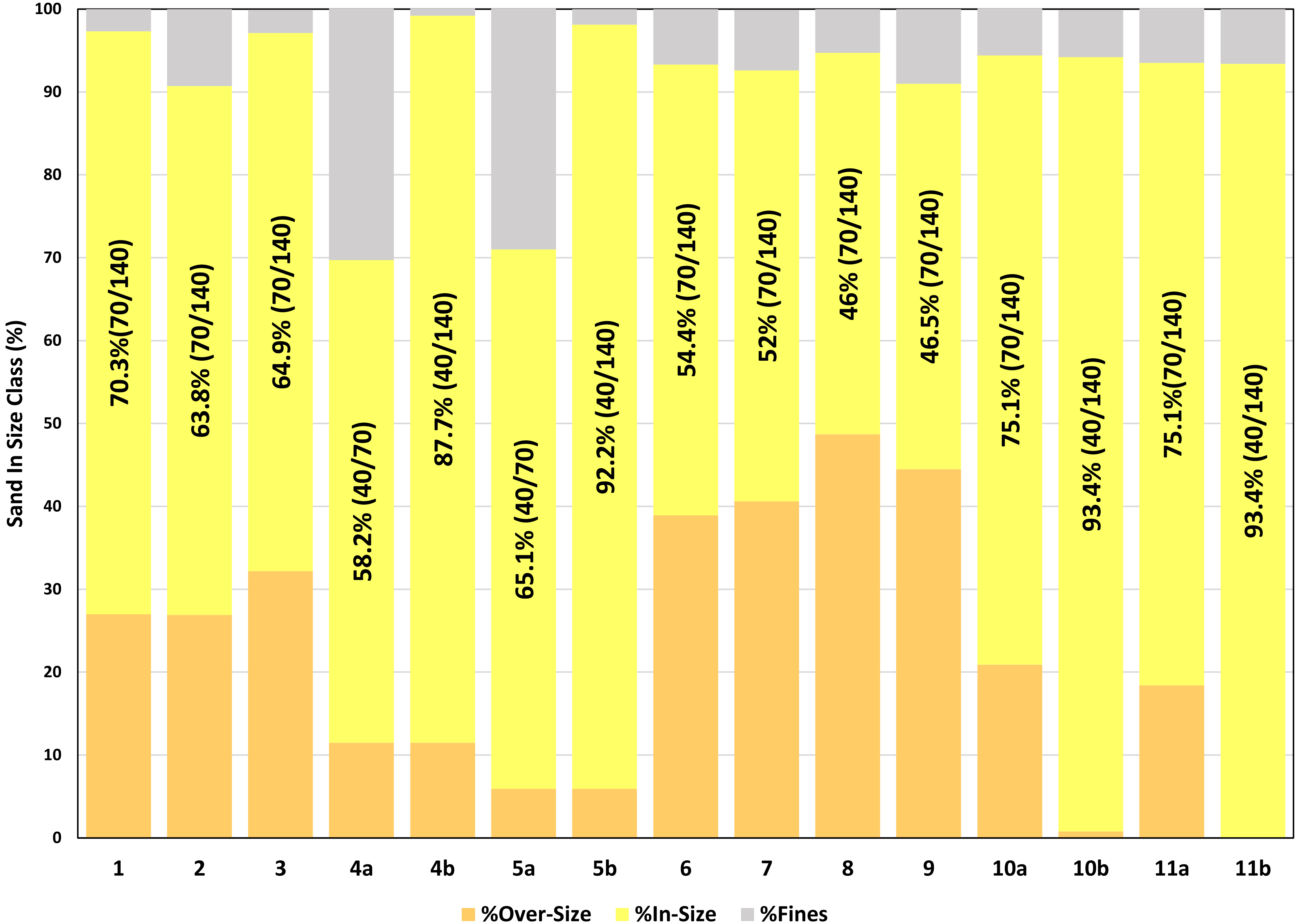

Figure 7. Comparison of the amounts of sand in tested size class (wt. %) for windblown sand in eastern North Dakota.

Table 3. Proppant Testing Analytical Summary of Windblown Sands in Eastern 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	Pembina Dunes (PD-2)	70/140	68.1	5K	7.2	0.8	0.5	0.195	0.179	62	ND	81.3	1.60
2	Pembina Dunes (PD-3)	70/140	66.6	5K	7.7	0.8	0.5	0.191	0.170	19.3	ND	85.7	1.60
3	Pembina Dunes (PD-4)	70/140	70.9	5K	6.9	0.8	0.5	0.209	0.186	62.5	0.12	84.7	1.61
4a	Pembina Dunes (PD-5)	40/70	71.5	5K	6.1	0.8	0.4	0.293	0.260	10.5	0.21	89.0	1.66
4b	Pembina Dunes (PD-5)	40/140	67.7	9K	7.0	0.8	0.5	0.293	0.260	11.0	0.33	89.8	1.67
5a	Brampton Dunes North	40/70	72.8	5K	6.7	0.8	0.6	0.273	0.262	23.2	0.19	88.1	1.62
5b	Brampton Dunes North	40/140	71.4	7K	6.5	0.8	0.5	0.273	0.262	31.2	0.26	88.9	1.65
6	Brampton Dunes South	70/140	63.9	5K	6.6	0.8	0.5	0.203	0.190	63.4	0.33	84.4	1.61
7	LaMoure Southeast	70/140	63.4	5K	7.7	0.8	0.5	0.217	0.191	67.8	0.27	84.5	1.59
8	Edinburg Sands	70/140	65.0	5K	8.9	0.8	0.5	0.246	0.248	11.0	0.48	83.4	1.54
9	Larimore Sands	70/140	63.3	5K	9.6	0.8	0.5	0.219	0.198	12.8	0.91	82.6	1.52
10a	Hankinson Dunes	70/140	69.6	5K	7.2	0.8	0.5	0.178	0.170	12.3	0.34	85.0	1.60
10b	Hankinson Dunes	40/140	70.8	5K	7.5	0.8	0.5	0.178	0.170	10.2	0.58	85.8	1.63
11a	Sheyenne Dunes	70/140	67.2	5K	8.2	0.8	0.5	0.172	0.166	45.0	0.23	84.6	1.61
11b	Sheyenne Dunes	40/140	71.1	5K	7.1	0.8	0.5	0.172	0.166	39.7	0.31	85.3	1.62

[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 Gradational (Sieve) Analysis Results Summary (Weight % Retained)

Sample No.		1	2	3	4	5	6	7	8	9	10	11
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
	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	30	0.0	0.3	0.4	2.5	0.3	0.0	0.6	1.5	0.3	0.0	0.0
	40	1.2	1.9	2.9	9.0	5.6	0.8	3.5	6.9	3.1	0.0	0.0
	45	2.3	2.5	3.1	10.0	10.7	2.7	4.7	7.5	5.0	0.3	0.1
	50	4.2	4.6	4.7	14.6	18.2	7.5	7.3	10.8	9.1	1.9	0.9
	60	7.3	6.9	8.2	17.9	21.8	12.9	11.7	11.9	14.3	6.4	5.7
	70	12.1	10.8	12.9	15.7	14.4	15.1	12.8	10.3	12.4	12.3	11.7
	80	22.9	16.9	22.3	14.8	11.2	17.3	15.4	11.7	13.2	22.0	20.6
	100	26.0	21.1	23.7	9.9	8.4	17.6	16.4	14.8	13.5	26.2	25.5
	120	15.4	16.3	13.4	3.6	4.9	12.4	12.6	12.3	11.8	17.2	19.5
	140	6.0	9.5	5.4	1.2	2.7	7.0	7.6	7.2	8.1	8.1	9.6
	170	2.0	5.4	2.0	0.5	1.2	3.9	4.1	3.4	4.7	3.8	4.2
	200	0.6	3.2	0.8	0.3	0.6	2.3	2.5	1.6	3.5	1.6	2.0
	Pan	0.1	0.6	0.1	0.1	0.1	0.5	0.7	0.2	0.8	0.3	0.4
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

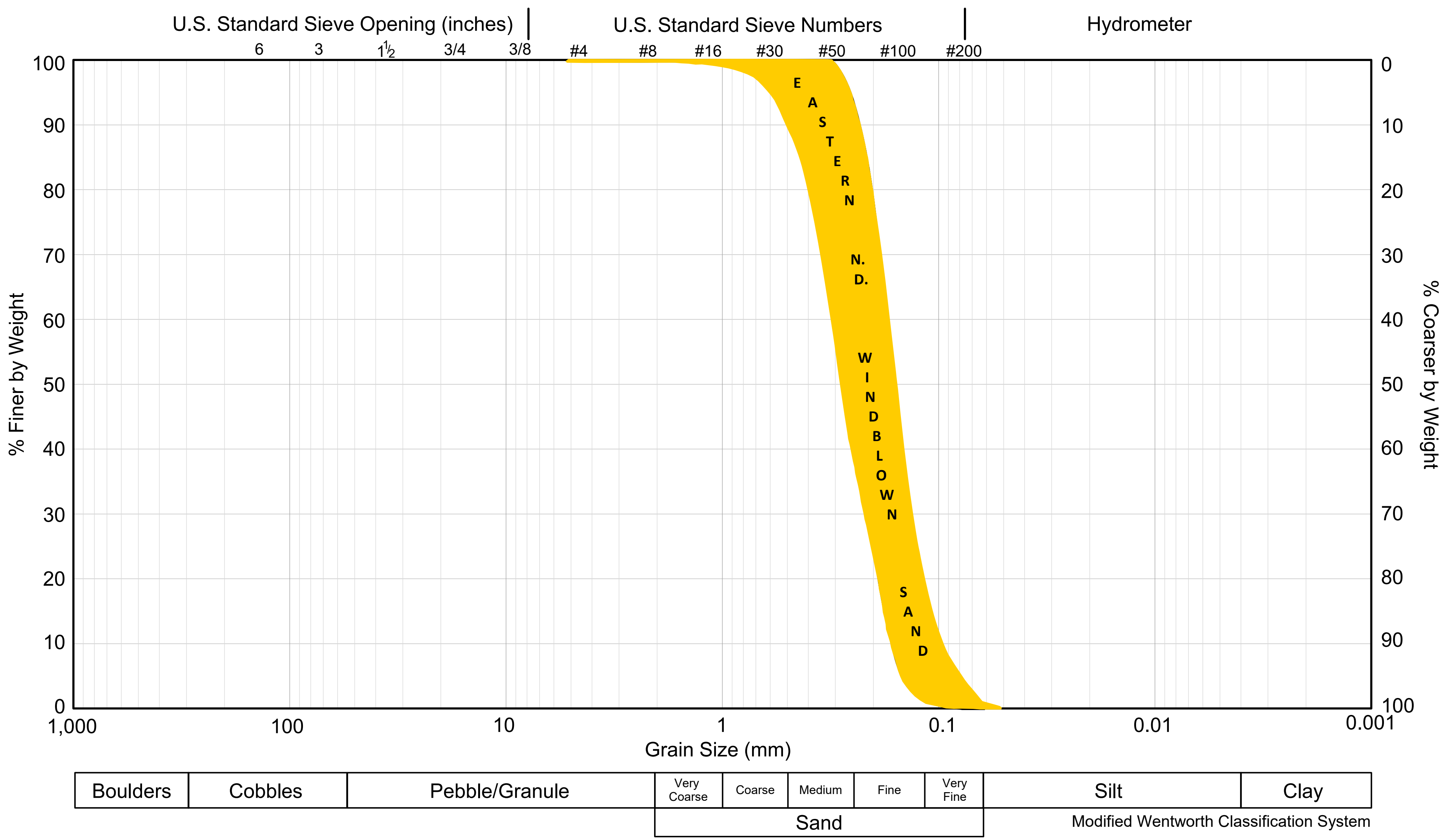

Figure 8. Range of 11 grain-size distribution curves (shaded-yellow) from windblown dune deposits in eastern North Dakota. These sands are well sorted and medium to very-fine grained according to the Modified Wentworth Classification System.

Table 5. Percent Sand in Size Class Summary*

Sample No.	Sand Deposit Area	Sand in Size Class (%)				
		30/50	40/70	70/140	50/140	40/140
1	Pembina Dunes	7.3	24.7	67.3	85.8	91.9
2	Pembina Dunes	8.3	23.0	59.2	75.6	82.2
3	Pembina Dunes	10.2	27.6	61.9	82.1	89.6
4	Pembina Dunes	32.5	56.4	28.6	61.2	85.0
5	Brampton Dunes North	33.4	63.1	26.3	61.5	89.4
6	Brampton Dunes South	10.5	36.6	52.2	79.0	88.7
7	LaMoure Southeast	14.4	33.8	48.2	70.8	81.9
8	Edinburg Sands	19.5	31.3	35.7	52.8	67.0
9	Larimore Sands	10.4	24.6	28.0	44.1	52.7
10	Hankinson Dunes	2.0	19.3	68.1	85.4	87.4
11	Sheyenne Dunes	0.9	16.6	67.8	83.5	84.4

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

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 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 eastern North Dakota had sphericity values generally equal to 0.5 with roundness values consistently at 0.8 (Figure 9). These values approach desired specifications, particularly for roundness factors, but are less spherical in grain character as compared to the windblown sand deposits found in central North Dakota.

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 10) but are consistent with other windblown sands in central North Dakota (Anderson, 2020a & b) and are considerably lower than other sand sources tested in North Dakota (Anderson and others, 2019). Acid solubility on these eolian sands ranged from 6.1 to 9.6% (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 15 samples were below the recommended limit of 250 FTU (Figure 11). The samples ranged from 10.2 to 67.8 FTU (Table 3), similar to other tested sand in north-central North Dakota (Anderson, 2020b) and lower than sand tested from south-central North Dakota (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 11 samples plus additional testing on 40/140 sand from the Pembina, Sheyenne, Hankinson, and Brampton (Riverdale Ridge) Dunes (4b, 5b, etc.). 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 were consistently at 5,000 psi (5K) within the 40/70 and 70/140 size classes (Table 6). Two of the 40/140 samples from the Pembina and Brampton (Riverdale Ridge) North Dunes returned K-values at 9K and 7K, respectively. This is likely due to the degradation of larger grain sizes in the sample during testing. Ottawa White sands typically generate K-values between 7-15K. Bakken oil and gas wells have fracture closure stresses in the reservoir that range typically around 9,500 psi. Perhaps by selecting a broader range of grain size for proppant use, higher crush resistance could be achieved.

Loss on Ignition Testing

Loss on ignition (LOI) testing was performed on selected sample size cuts to serve as a proxy for determination of the potential detrital lignite content. The LOI values were all low, ranging from no detect (ND) to 0.91%, which is probably to be expected from a washed, sized sample cut (Table 3, Figure 12). This suggests a very low amount of potential organic based deleterious constituents.

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 63 to 73%, feldspar ranged from 25 to 34%, and clay contents ranged from 0 to 3.3% (Figure 13). 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 one *bulk* sand sample (i.e., meaning samples that have not been washed and sized) from the Pembina Dunes to provide additional information of overall mineralogical character on deposits in situ (Appendix III). In this analysis clay content was low at 2%, and micas were reported at 3% (Table A-III-1). Quartz and feldspar contents were consistent with washed samples at 70% and 25% respectively. No carbonates or iron containing minerals were detected in the bulk sample, further suggesting a low potential for the existence of potentially deleterious mineralogy to be present in the windblown deposits.

Table 6. Crush Resistance Testing Data Summary

Sample No.	Size Class	K-Value	Test Stress (psi)							
			3000	4000	5000	6000	7000	8000	9000	10000
			Fines Generated (%)							
1	70/140	5K	--	--	7.39	10.48	--	--	--	--
2	70/140	5K	--	--	5.59	10.27	--	--	--	--
3	70/140	5K	--	--	8.10	11.21	--	--	--	--
4a	40/70	5K	--	--	8.10	12.15	--	--	--	--
4b	40/140	9K	--	--	--	--	--	--	9.23	10.94
5a	40/70	5K	--	--	8.27	11.71	--	--	--	--
5b	40/140	7K	--	--	--	--	7.52	10.13	--	--
6	70/140	5K	--	--	7.74	10.99	--	--	--	--
7	70/140	5K	--	--	8.84	13.11	--	--	--	--
8	70/140	5K	--	--	9.18	13.11	--	--	--	--
9	70/140	5K	--	--	9.41	12.29	--	--	--	--
10a	70/140	5K	--	--	9.74	11.92	--	--	--	--
10b	40/140	5K	--	--	8.91	10.53	--	--	--	--
11a	70/140	5K	--	--	8.62	10.80	--	--	--	--
11b	40/140	5K	--	--	8.22	11.13	--	--	--	--

-- Stress point not tested. Crush resistance testing performed on largest representative sand size class in sample.

Bulk Density

In regard to 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 (Figure 1, Table 3) ranged from 81 to 90 pounds per cubic foot (pcf) with an average of 86 pcf.

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 windblown sands, ranged from 1.5 to 1.7 grams per cubic centimeter (g/cm^3) with an average of 1.6 g/cm^3 (Figure 1, Table 3). Absolute density values are used in the design of hydraulic fracturing applications. A summary of proppant testing specifications is provided in Appendix IV.

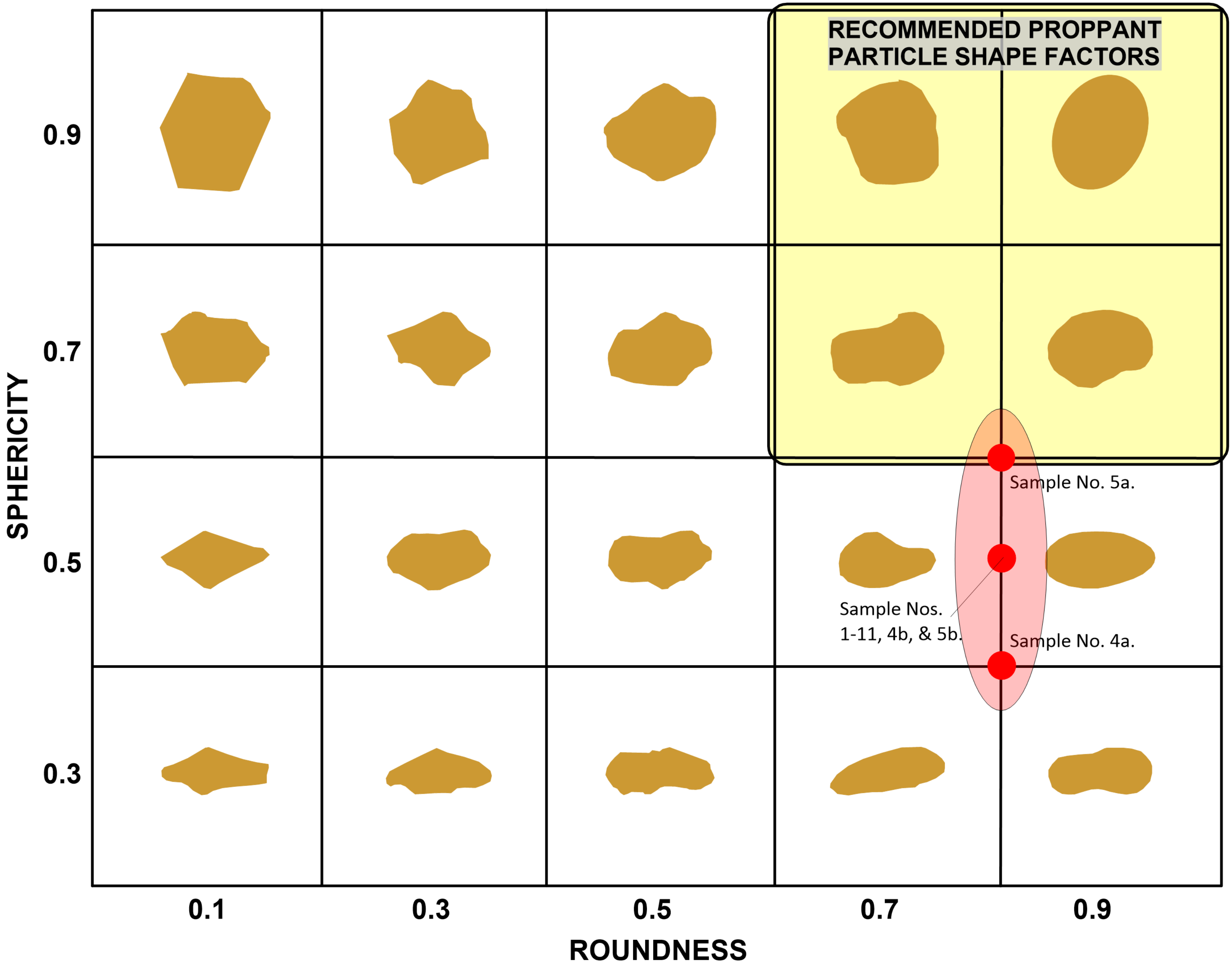

Figure 9. Comparison of sphericity and roundness values for windblown sand samples from eastern North Dakota. Samples from these deposits have particle shape factor values (shaded pink) that approach the range of desired specifications (shaded yellow) for frac sand as compared to Ottawa White silica sands.

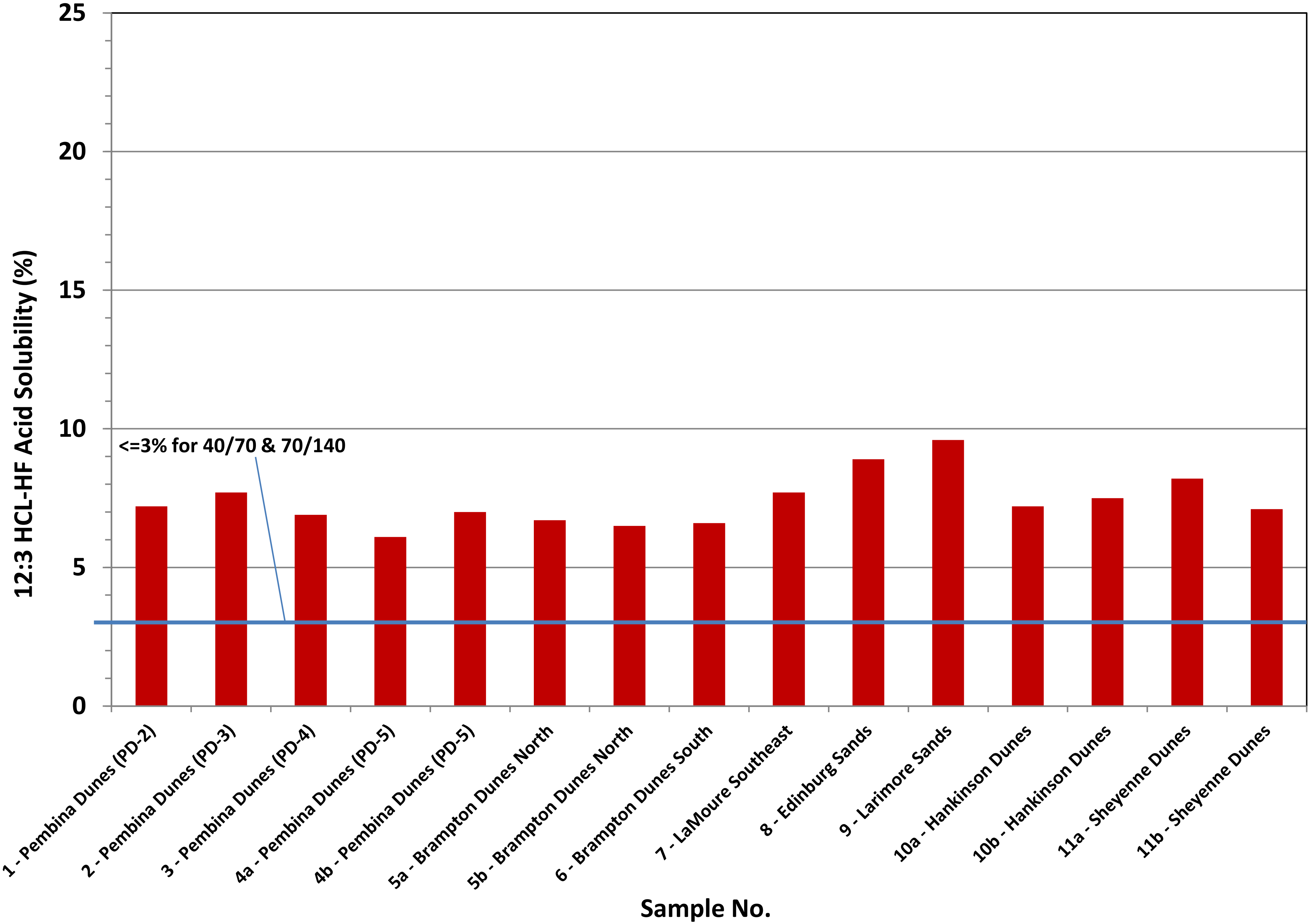

Figure 10. Comparison of hydrochloric:hydrofluoric acid solubility results for windblown sand deposits in eastern North Dakota. Recommended specifications for acid solubility on 40/70 & 70/140 sands are less than or equal to 3% (blue line).

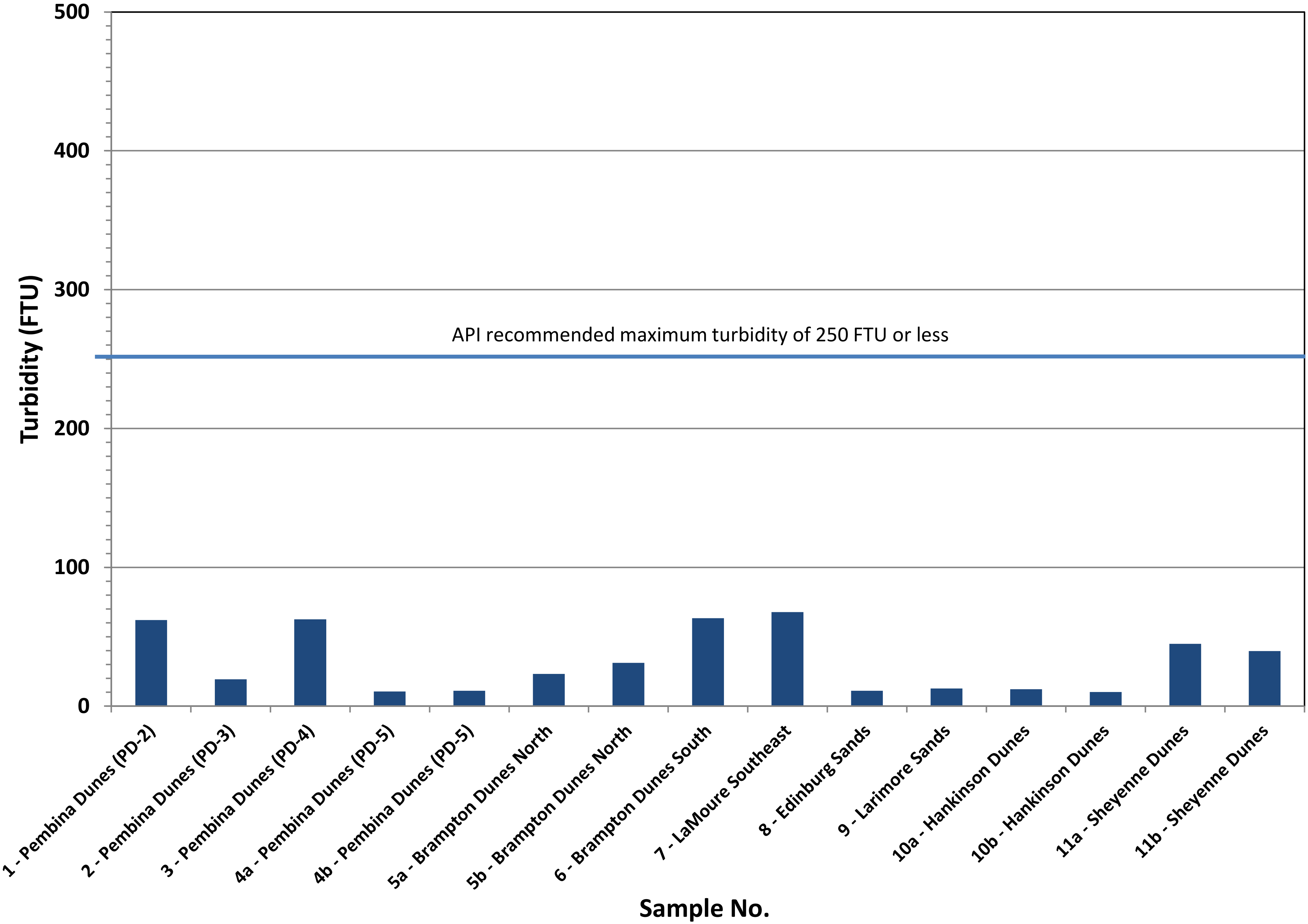

Figure 11. Comparison of turbidity results for washed sand samples from windblown sand deposits in eastern North Dakota. Recommended API specifications for turbidity are 250 FTU or less (blue line). All samples tested are well below this criteria.

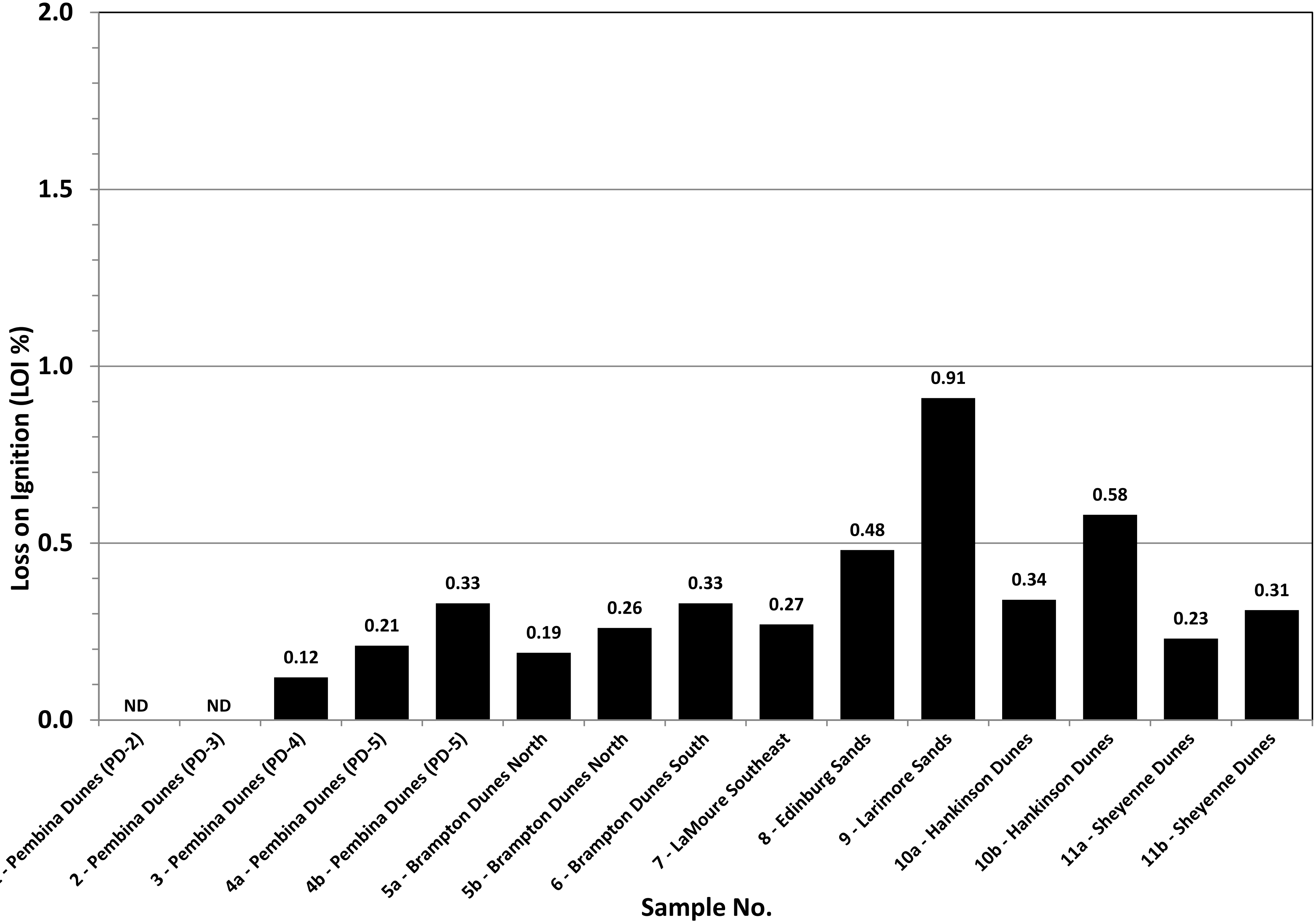

Figure 12. Graph of loss on ignition (LOI) values of windblown sand from eastern North Dakota deposits. These sands are from the 40/70, 70/140, and 40/140 size classes which are washed samples. The majority of samples are all less than 0.5 % LOI which indicates a low overall organic content. ND = Not Detected.

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

Sample ID	Sand Deposit Area	Tested Size Class	Quartz	Feldspars			Clays		Carbonates			Other Minerals
				Albite	Microcline	Feldspars*	Illite	Clays*	Calcite	Dolomite	Carbonates*	
1	Pembina Dunes	70/140	68.1	20.2	10.1	30.3	1.6	1.6	--	--	--	NR
2	Pembina Dunes	70/140	66.6	17.6	14.0	31.6	1.8	1.8	--	--	--	NR
3	Pembina Dunes	70/140	70.9	16.5	10.4	26.9	2.2	2.2	--	--	--	NR
4a	Pembina Dunes	40/70	71.5	17.0	9.5	26.5	2.0	2.0	--	--	--	NR
4b	Pembina Dunes	40/140	67.7	19.1	10.8	29.9	2.4	2.4	--	--	--	NR
5a	Brampton Dunes North	40/70	72.8	15.9	9.4	25.3	1.9	1.9	--	--	--	NR
5b	Brampton Dunes North	40/140	71.4	16.4	9.1	25.5	3.1	3.1	--	--	--	NR
6	Brampton Dunes South	70/140	63.9	19.3	14.1	33.4	2.7	2.7	--	--	--	NR
7	LaMoure County Southeast	70/140	63.4	25.1	8.2	33.3	3.3	3.3	--	--	--	NR
8	Edinburg Sands	70/140	65.0	21.1	11.7	32.8	2.2	2.2	--	--	--	NR
9	Larimore Sands	70/140	63.3	22.4	11.6	34.0	2.8	2.8	--	--	--	NR
10a	Hankinson Dunes	70/140	69.6	18.2	11.4	29.6	0.9	0.9	--	--	--	NR
10b	Hankinson Dunes	40/140	70.8	17.9	8.7	26.6	2.6	2.6	--	--	--	NR
11a	Sheyennne Dunes	70/140	67.2	19.2	11.4	30.6	2.2	2.2	--	--	--	NR
11b	Sheyennne Dunes	40/140	71.1	17.8	8.8	26.6	2.3	2.3	--	--	--	NR

** Undifferentiated*

-- Mineral not detected

NR Not Reported

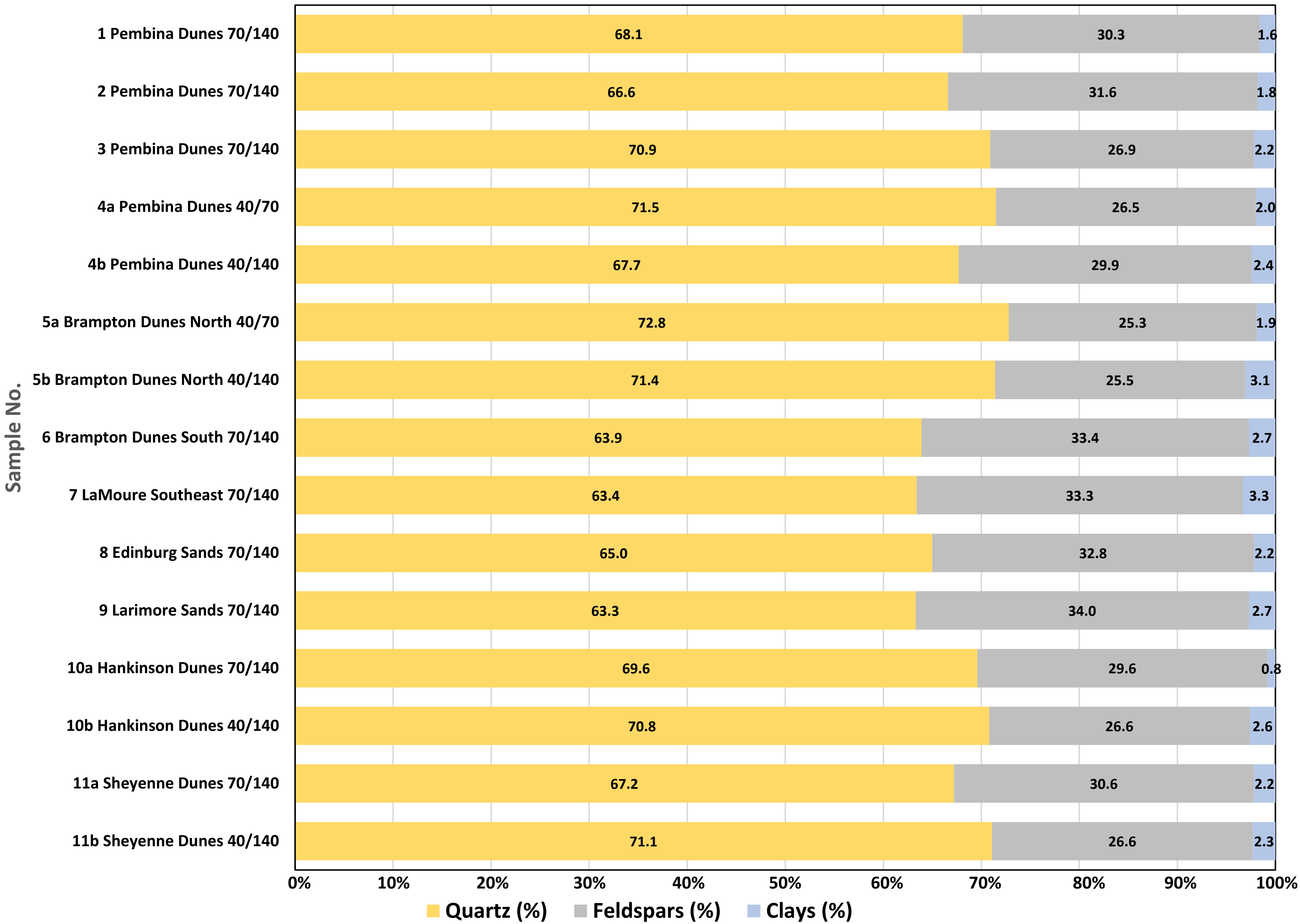

Figure 13. Summary mineralogy (weight %) of processed (washed and sized) sand from X-ray diffraction (XRD) analysis of windblown sand deposits in eastern North Dakota. No carbonates were reported in any of the samples analyzed.

CONCLUSIONS

Windblown sand deposits in eastern 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 central North Dakota. These deposits are found in low and high-relief sand dunes in localized coalesced dune fields and wind scoured sheet sands of limited thickness. The dune fields in the Pembina, Sheyenne, Hankinson, and southwestern Sargent County areas contain the most abundant windblown deposits. The sand is well sorted with grain size ranges dominantly in the finer size classes (70/140) with an average of 68% quartz in the washed and sized sand portions. Crush resistance is consistent at 5,000 psi (5K) in the 40/70 and 70/140 sand sizes. The 40/140 cuts returned higher crush resistance values of 7,000 (7K) and 9,000 psi (9K) presumably due to the degradation of larger grains within samples. Particle shape factors for these sand grains also approach desired industry specifications for sphericity and roundness, but are lower than deposits in Mercer and McHenry Counties. Sand quality is consistent across all the deposits tested as no regionality was observed in the testing data. The testing data included in this report should prove valuable for other potential industrial sand uses as well as future sedimentological research in windblown environments.

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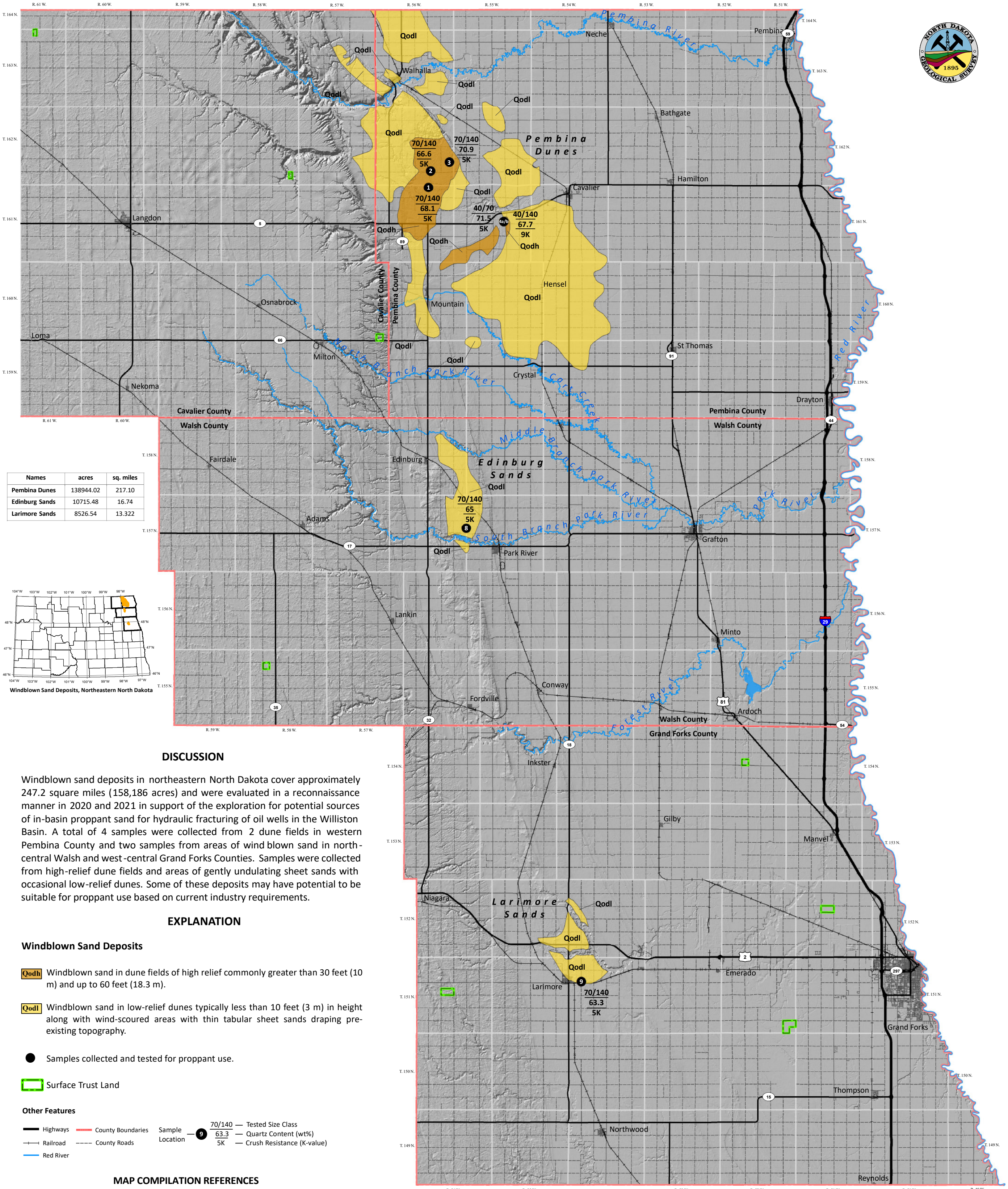
North Dakota Geological Survey
Report of Investigation No. 127 - Plate I

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

Windblown Sand Deposits in Northeastern North Dakota



Names	acres	sq. miles
Pembina Dunes	138944.02	217.10
Edinburg Sands	10715.48	16.74
Larimore Sands	8526.54	13.322

DISCUSSION

Windblown sand deposits in northeastern North Dakota cover approximately 247.2 square miles (158,186 acres) and were evaluated in a reconnaissance manner in 2020 and 2021 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 4 samples were collected from 2 dune fields in western Pembina County and two samples from areas of wind blown sand in north-central Walsh and west-central Grand Forks Counties. 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
- Railroad
- Red River
- County Boundaries
- County Roads

Sample Location — 9 — 70/140 — Tested Size Class; 63.3 — Quartz Content (wt%); 5K — Crush Resistance (K-value)

MAP COMPILATION REFERENCES

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N
W E
S

Scale 1:250,000

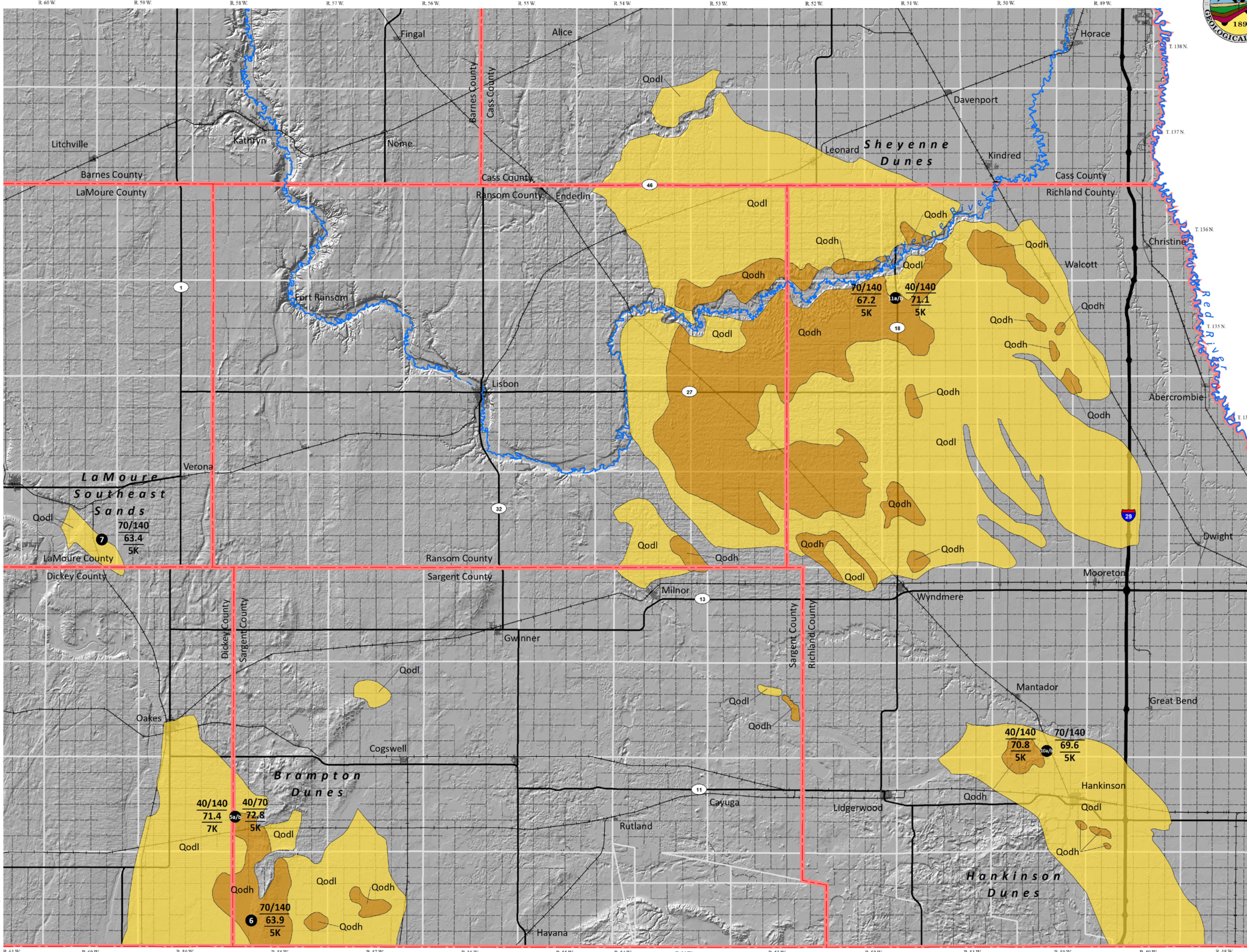
0 5 10

Miles

Mercator Projection
North American 1983 Datum
Central Meridian 98°0'0"W
Standard Parallel 1: 47°41'15"N

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

Windblown Sand Deposits in Southeastern North Dakota



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.

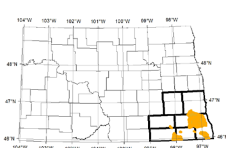
Surface Trust Land

Other Features

- Highways
- Railroad
- River
- County Boundaries
- County Roads

Sample Location — 6 — 70/140 — Tested Size Class; 63.9 — Quartz Content (wt%); 5K — Crush Resistance (K-value)

Names	acres	sq. miles
Brampton Dunes	99,335.36	155.21
LariMore SE Sands	4,302.19	6.72
Hankinson Sands	70,479.20	110.12
Sheyenne Dunes	448,190.85	700.30



Windblown Sand Deposits, SoutheasternNorth Dakota

N
W E
S

Scale 1:250,000

0 5 10

Miles

Mercator Projection
North American 1983 Datum
Central Meridian 98°0'0"E
Standard Parallel 1: 46°0'0"N

DISCUSSION

Windblown sand deposits in southeastern North Dakota cover approximately 972.36 square miles (622,308 acres) and were evaluated in a reconnaissance manner in 2020 and 2021 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 four samples were collected from three dune fields in southwestern Sargent and northwestern Richland Counties along with one sample from an area of windblown sand in southeastern LaMoure 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.

MAP COMPILATION REFERENCES

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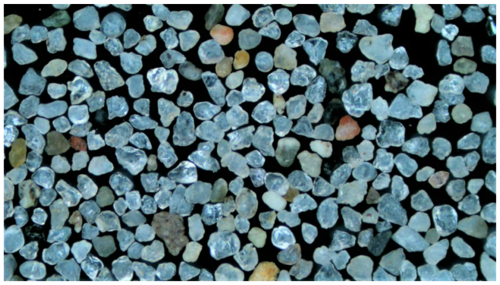
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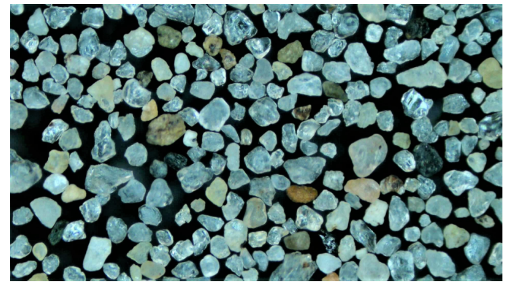
2. Pembina Dunes (PD-3) 70/140

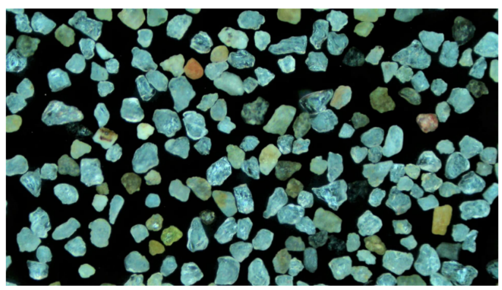

3. Pembina Dunes (PD-4) 70/140

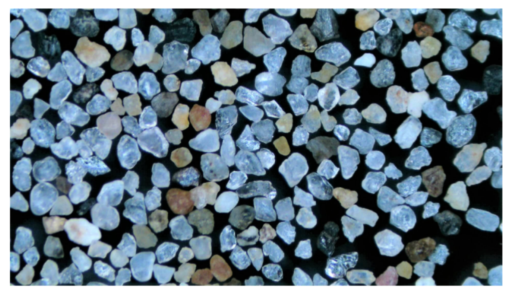

4. Pembina Dunes (PD-5) 40/70


5. Pembina Dunes (PD-5) 40/140


6. Brampton Dunes North 40/70

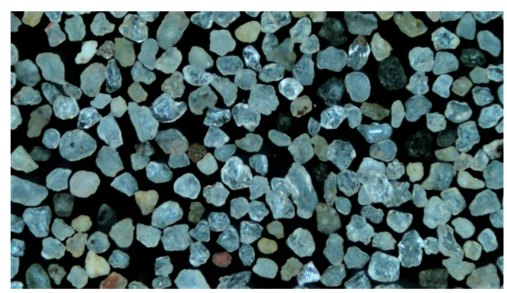

7. Brampton Dunes North 40/140

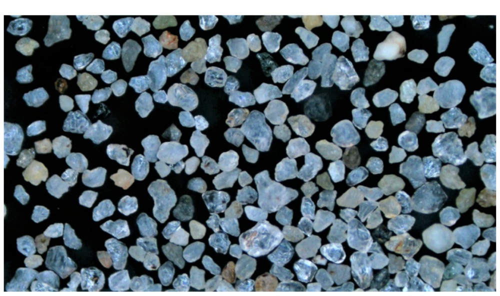

8. Brampton Dunes South 70/140

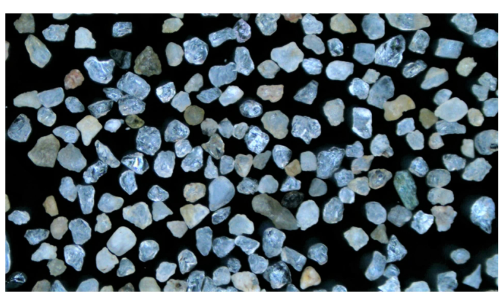

9. LaMoure County Southeast 70/140


10. Edinburg Sands 70/140


11. Larimore Sands 70/140


12. Hankinson Dunes 70/140


13. Hankinson Dunes 40/140


14. Sheyenne Dunes 70/140


15. Sheyenne Dunes 40/140

Plate III. Monolayer photomicrographs (40x) of windblown sand from dune and sheet sand deposits in eastern North Dakota.

Appendix I. Individual Grain-Size Distribution (Sieve) Diagrams of Windblown Sand Samples from Dune and Sheet Sand Deposits in Eastern 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.

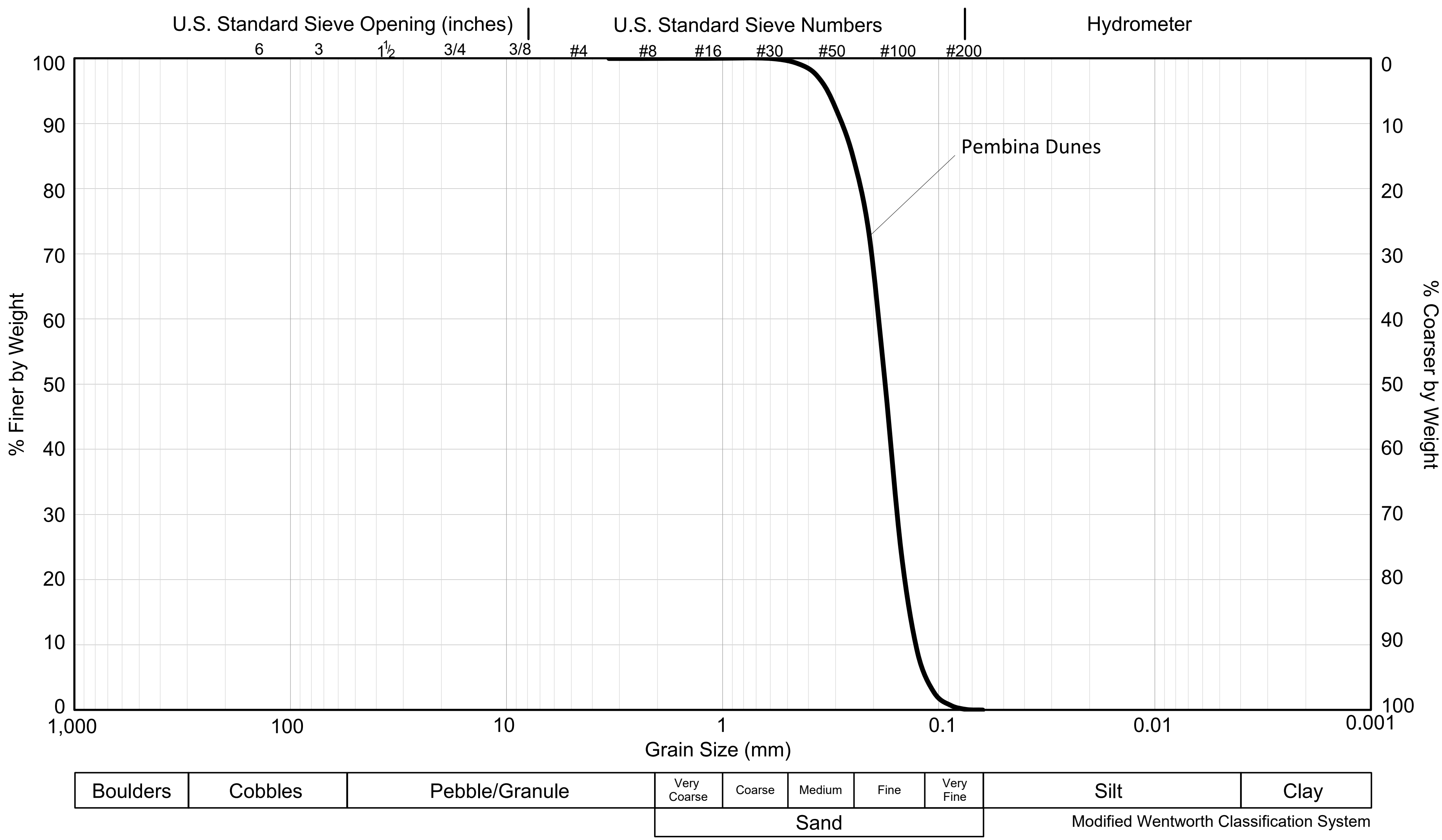


Figure A-I-1. Grain-size distribution diagram (sieve analysis) for Sample No. 1 from the Pembina Dunes.

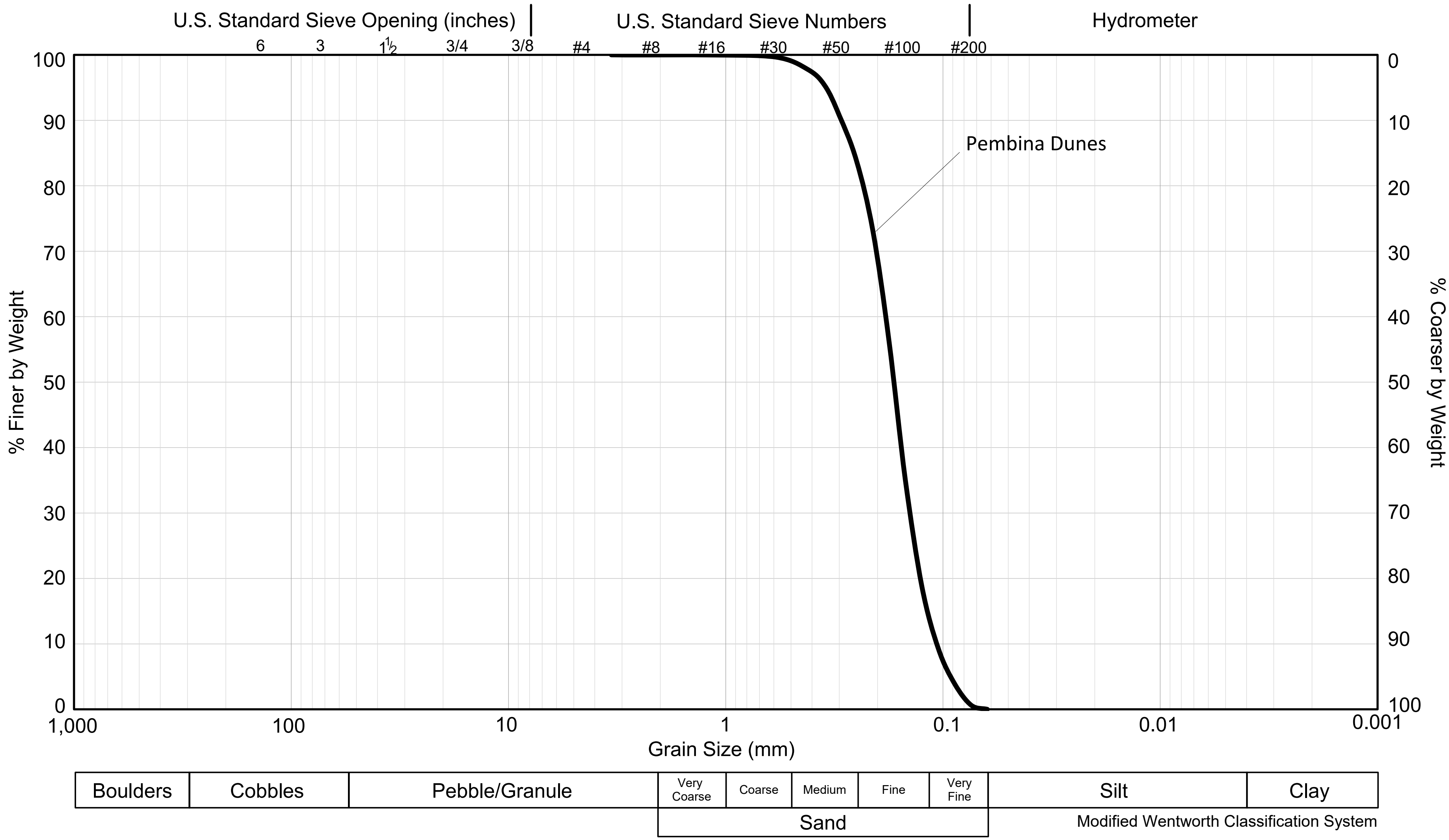


Figure A-I-2. Grain-size distribution diagram (sieve analysis) for Sample No. 2 from the Pembina Dunes.

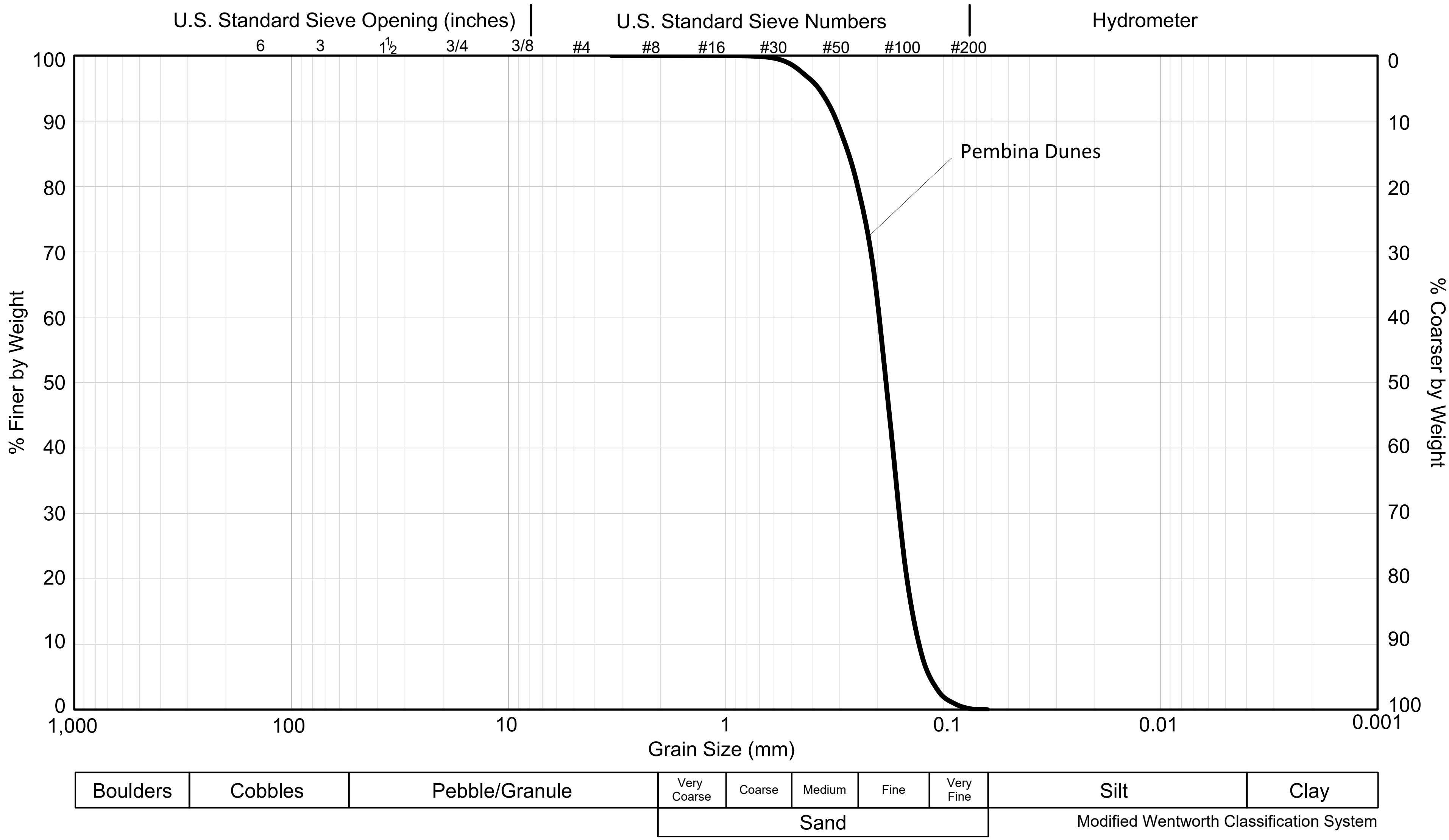


Figure A-I-3. Grain-size distribution diagram (sieve analysis) for Sample No. 3 from the Pembina Dunes.

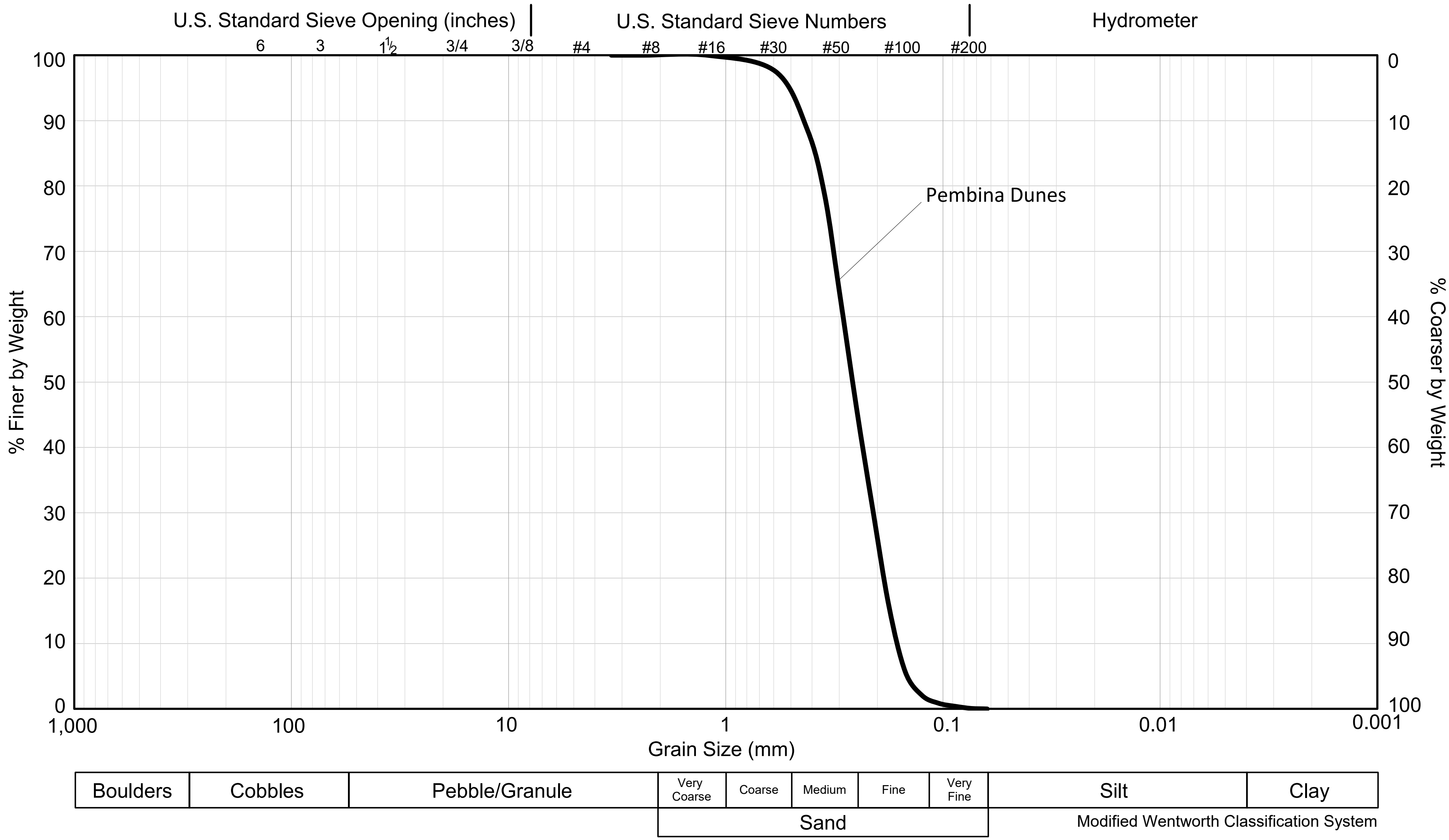


Figure A-I-4. Grain-size distribution diagram (sieve analysis) for Sample No. 4 from the Pembina Dunes.

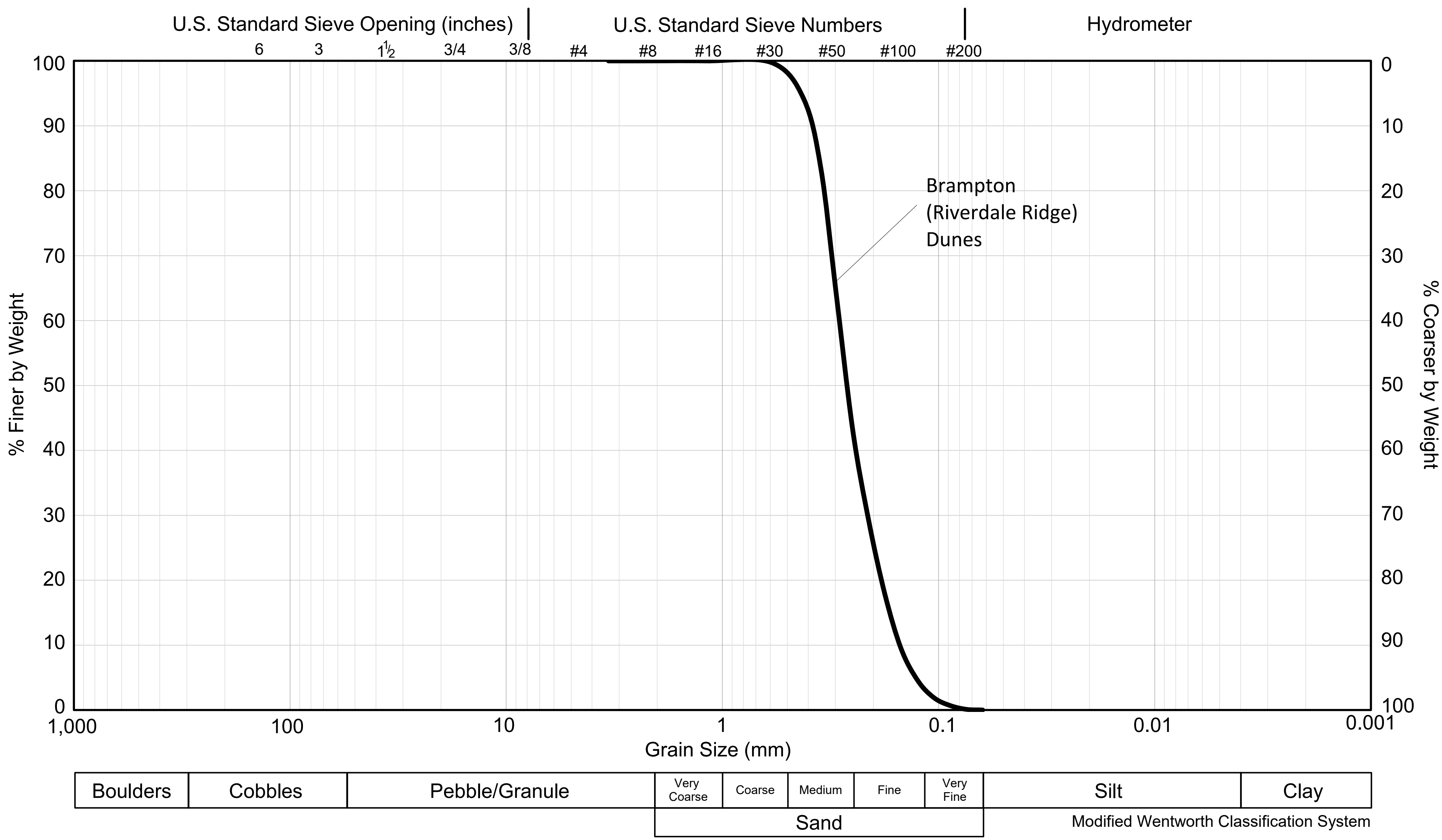


Figure A-I-5. Grain-size distribution diagram (sieve analysis) for Sample No. 5 from the Brampton (Riverdale Ridge) Dunes.

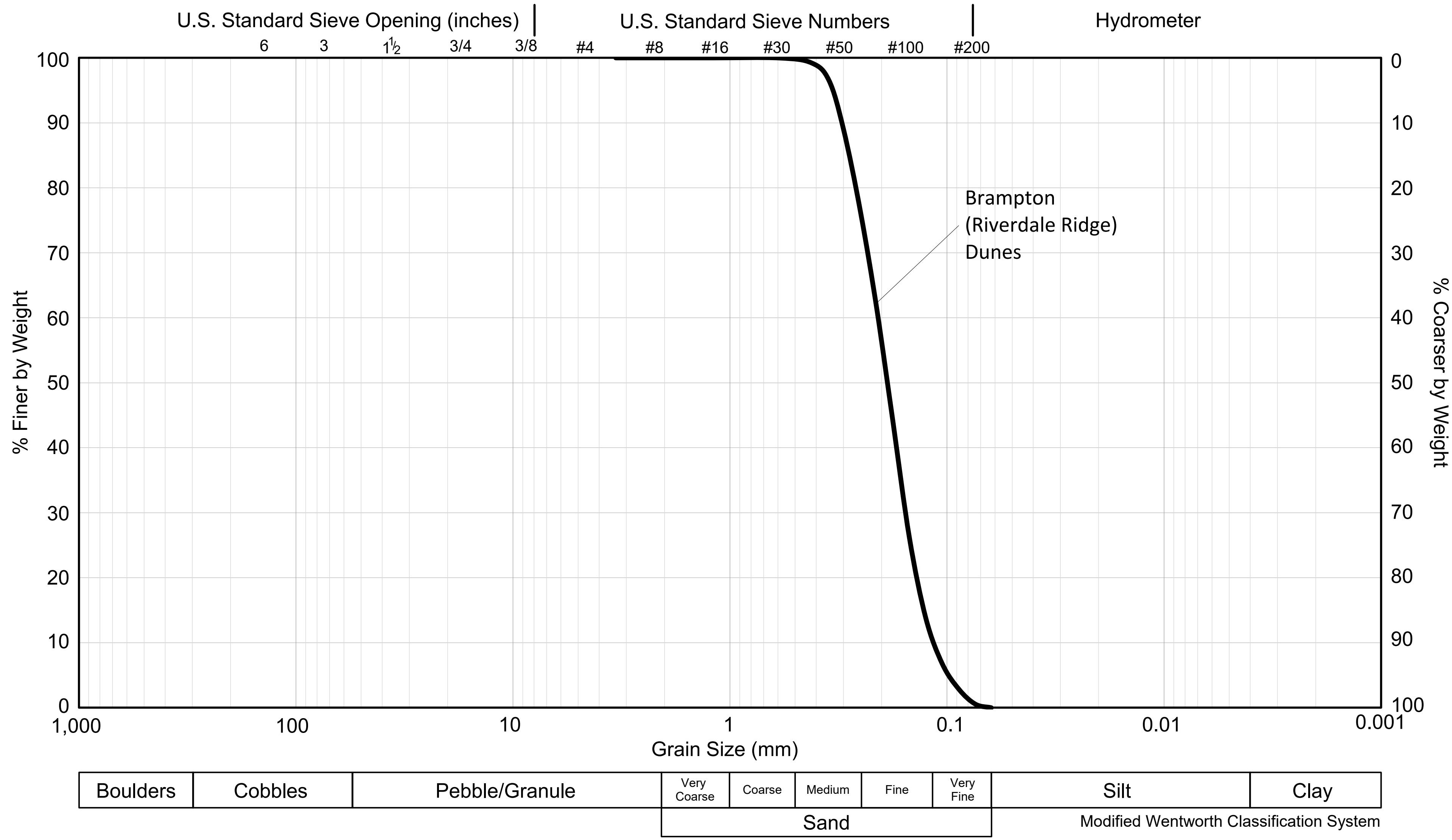


Figure A-I-6. Grain-size distribution diagram (sieve analysis) for Sample No. 6 from the Brampton (Riverdale Ridge) Dunes.

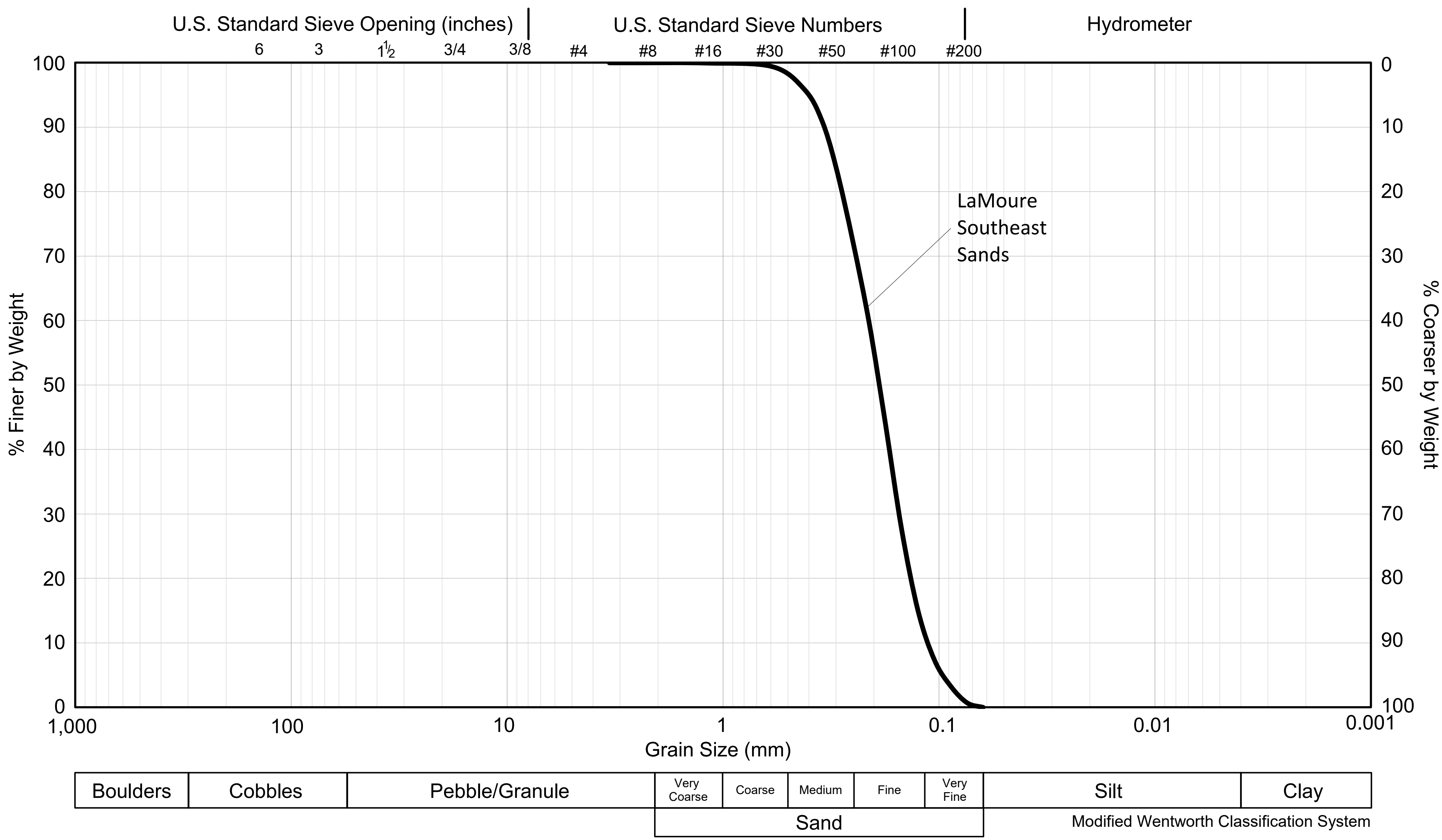


Figure A-I-7. Grain-size distribution diagram (sieve analysis) for Sample No. 7 from the LaMoure Southeast Sands.

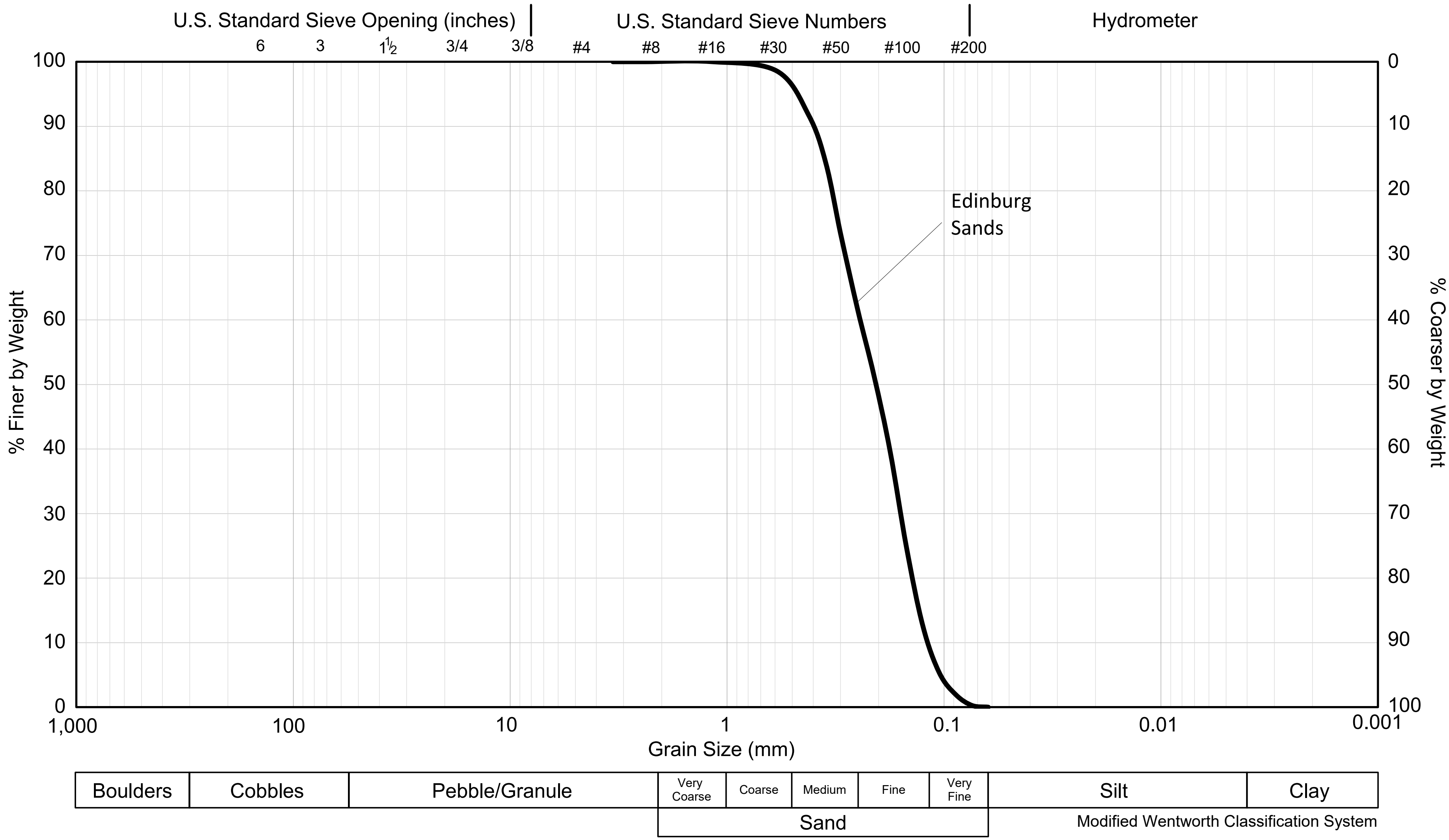


Figure A-I-8. Grain-size distribution diagram (sieve analysis) for Sample No. 8 from the Edinburg Sands.

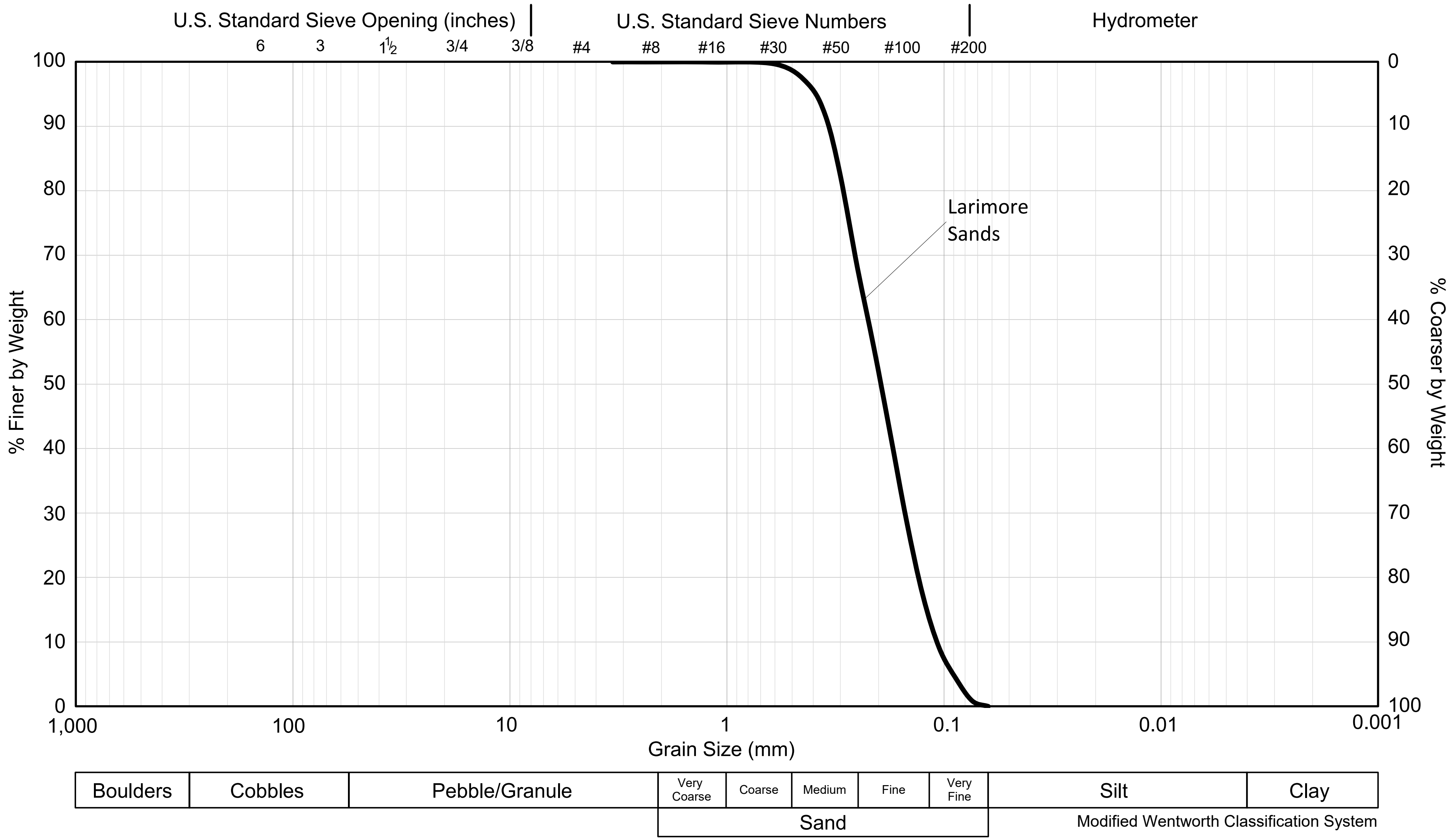


Figure A-I-9. Grain-size distribution diagram (sieve analysis) for Sample No. 9 from the Larimore Sands.

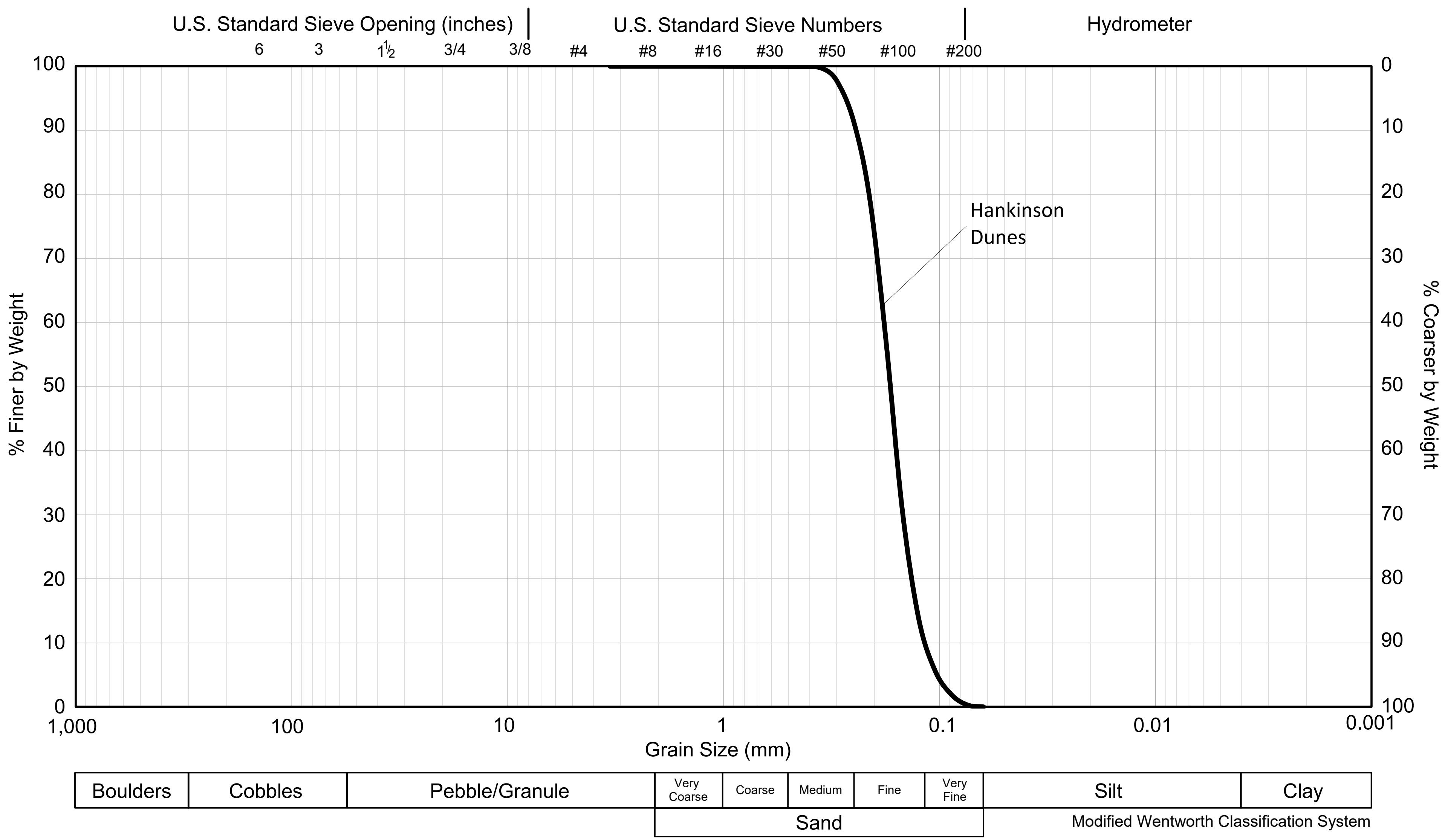


Figure A-I-10. Grain-size distribution diagram (sieve analysis) for Sample No. 10 from the Hankinson Dunes.

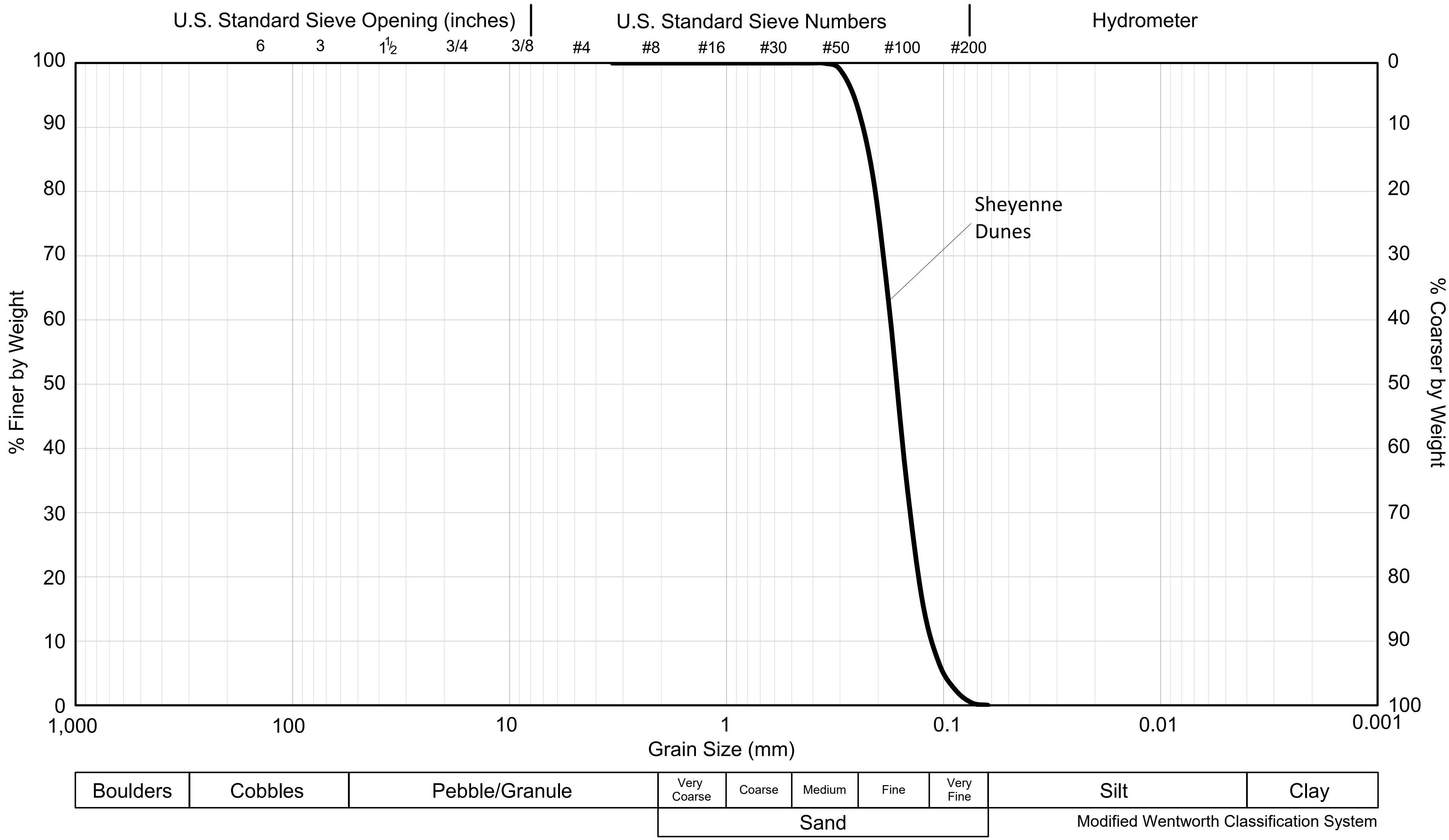


Figure A-I-11. Grain-size distribution diagram (sieve analysis) for Sample No. 11 from the Sheyenne Dunes.

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

Introduction

Sampling of sand from windblown deposits in eastern, North Dakota was completed in 2020 and 2021 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 11 samples from 11 locations were collected from high-relief dune fields found in Pembina, Sargent and Richland Counties in eastern North Dakota and areas of windblown sheet sands found in Walsh, Grand Forks, and LaMoure Counties. 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-15 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 sand sample no. 1 from the northern Pembina Dunes in northwestern Pembina County, North Dakota.

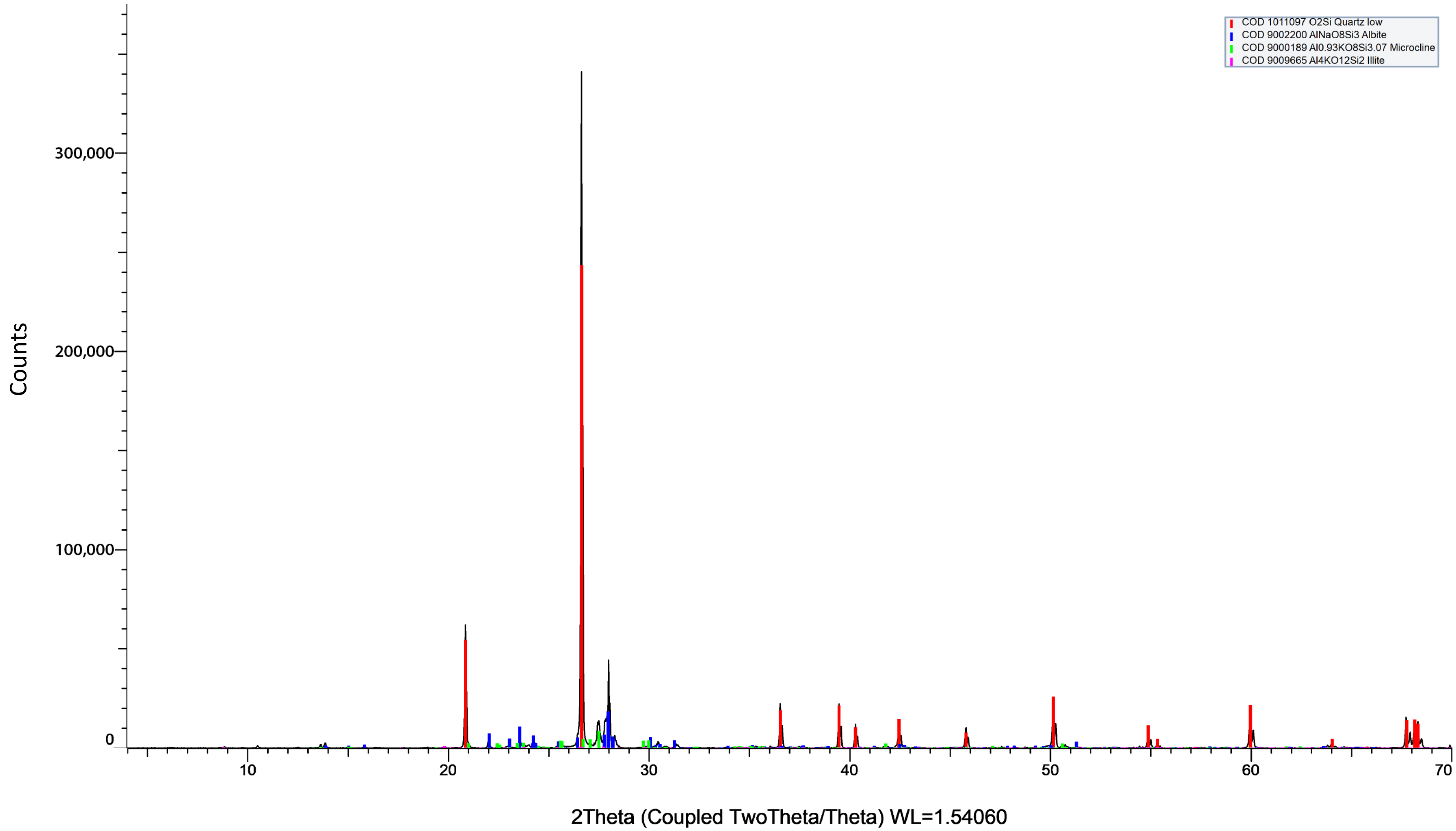


Figure A-II-2. XRD phase diagram of sand sample no. 2 from the northern Pembina Dunes in northwestern Pembina County, North Dakota.

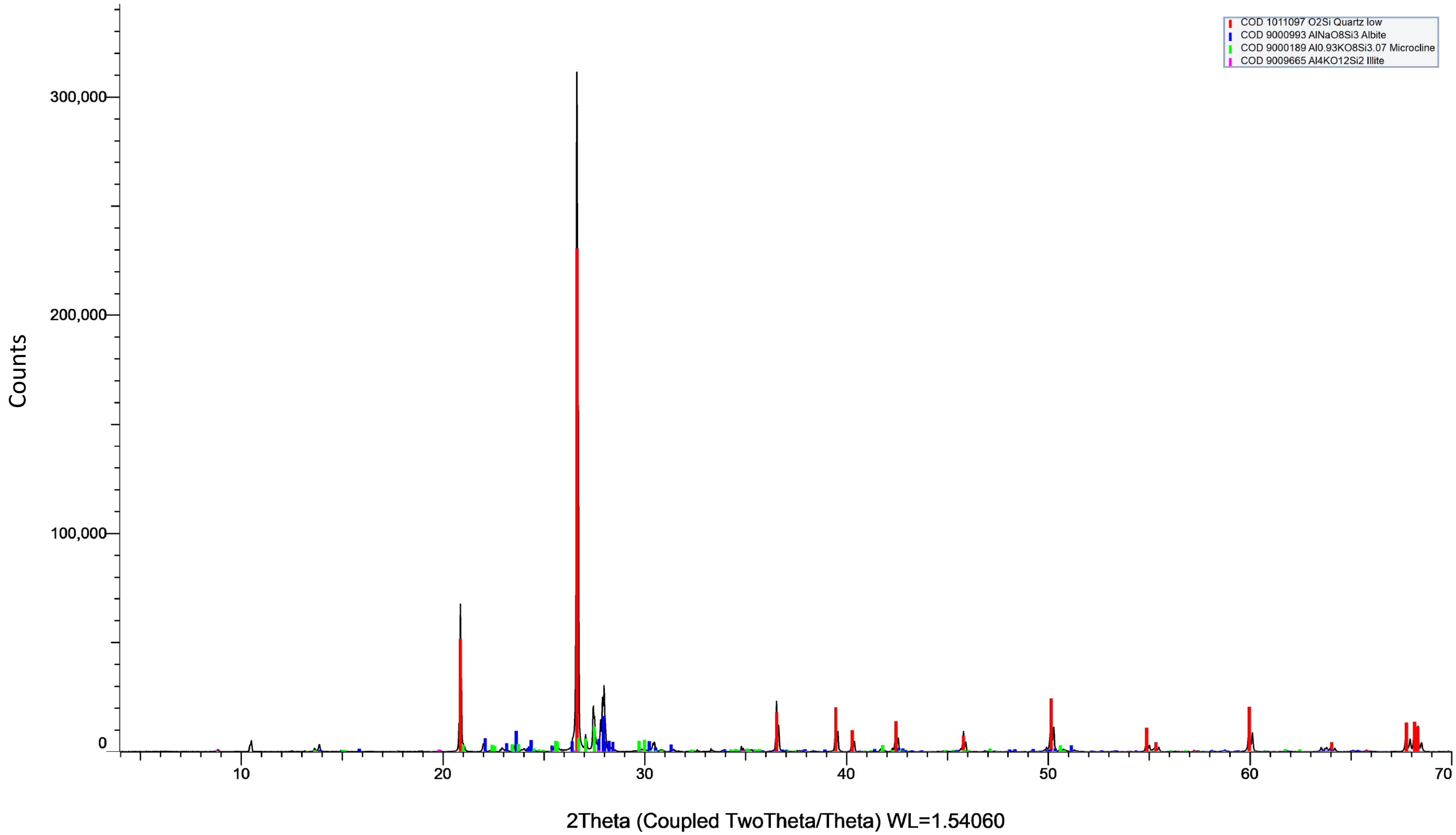


Figure A-II-3. XRD phase diagram of sand sample no. 3 from the northern Pembina Dunes in northwestern Pembina County, North Dakota.

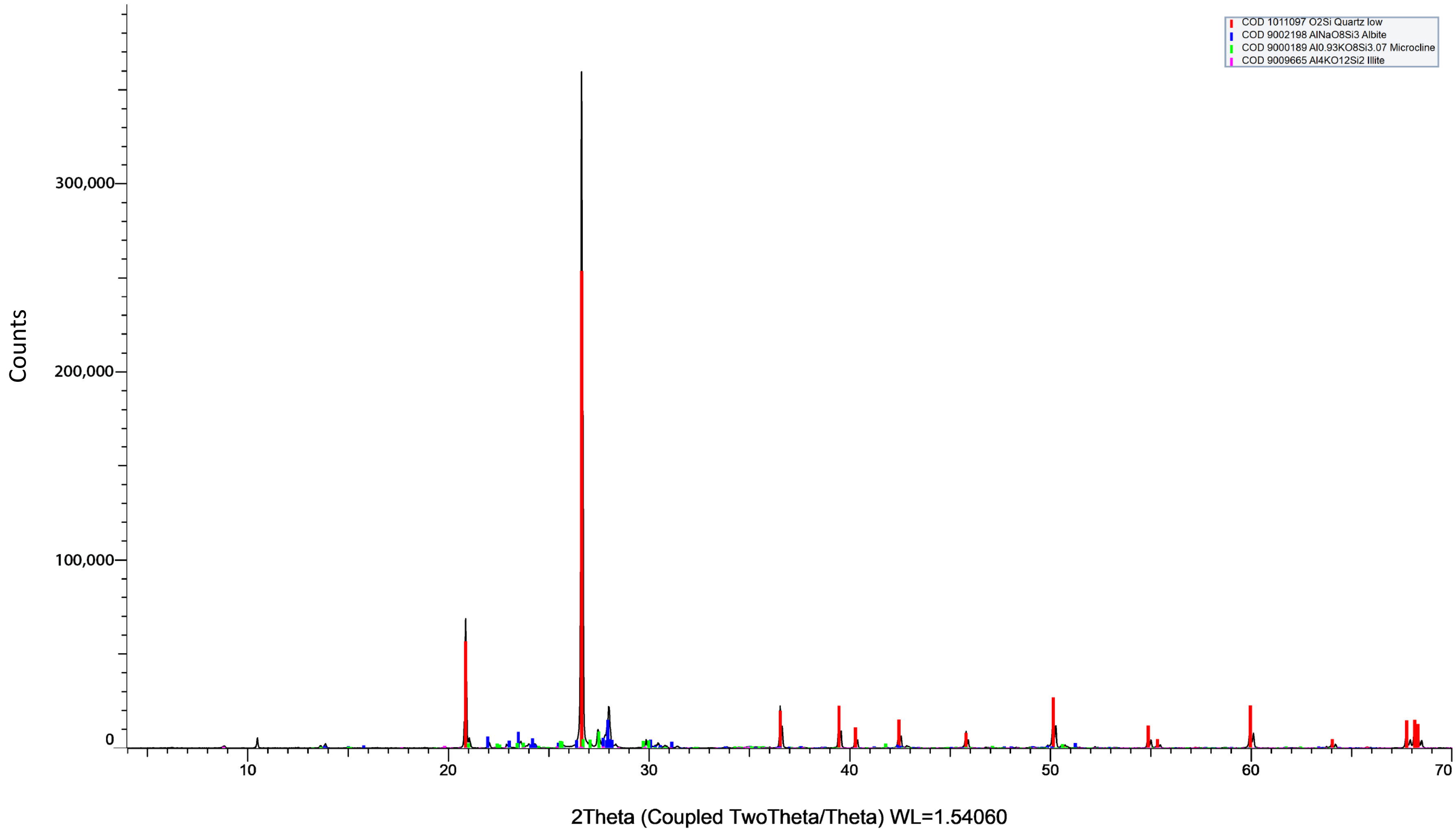


Figure A-II-4. XRD phase diagram of sand sample no. 4a from the southern Pembina Dunes in northwestern Pembina County, North Dakota.

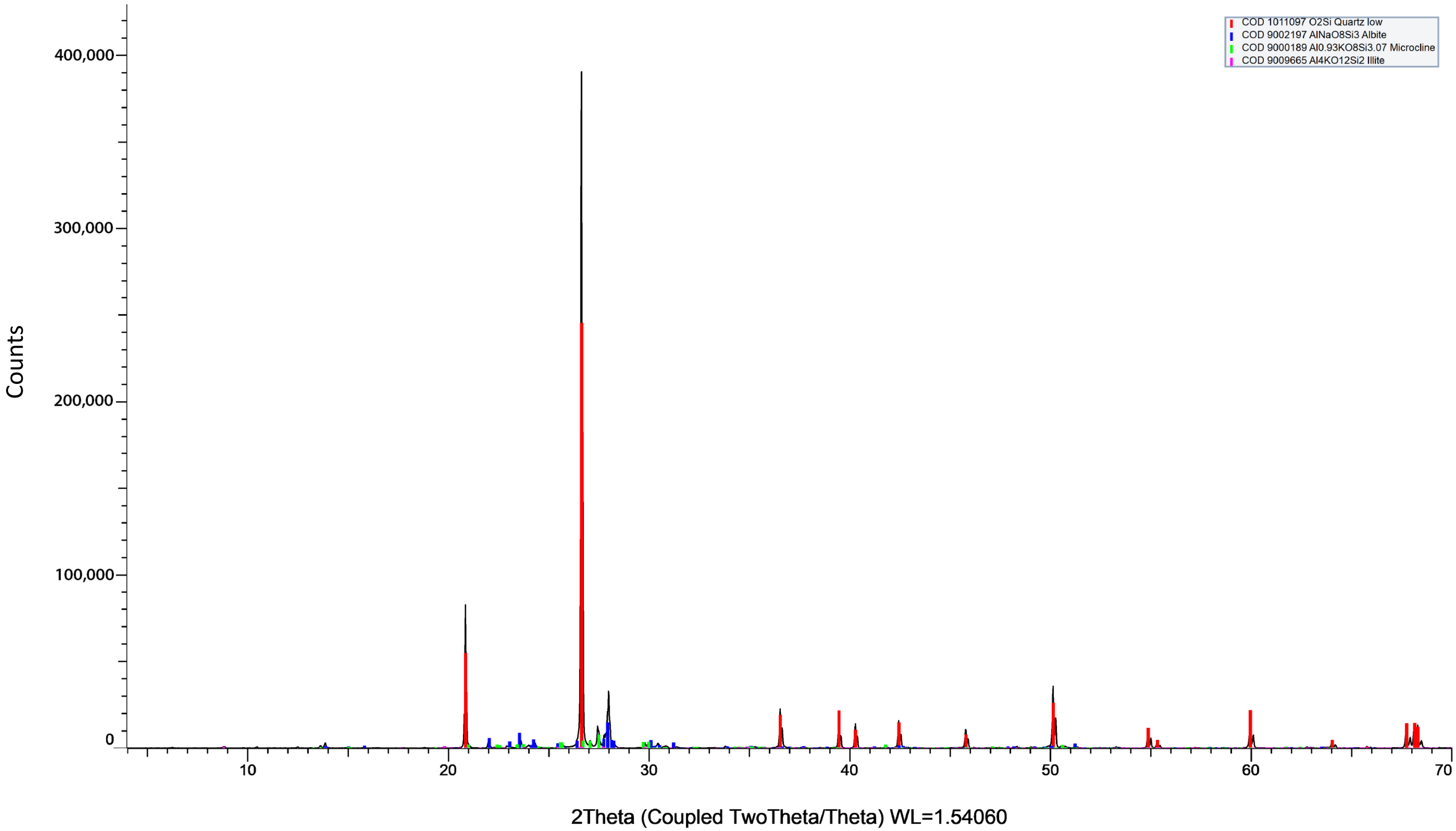


Figure A-II-5. XRD phase diagram of sand sample no. 4b from the southern Pembina Dunes in northwestern Pembina County, North Dakota.

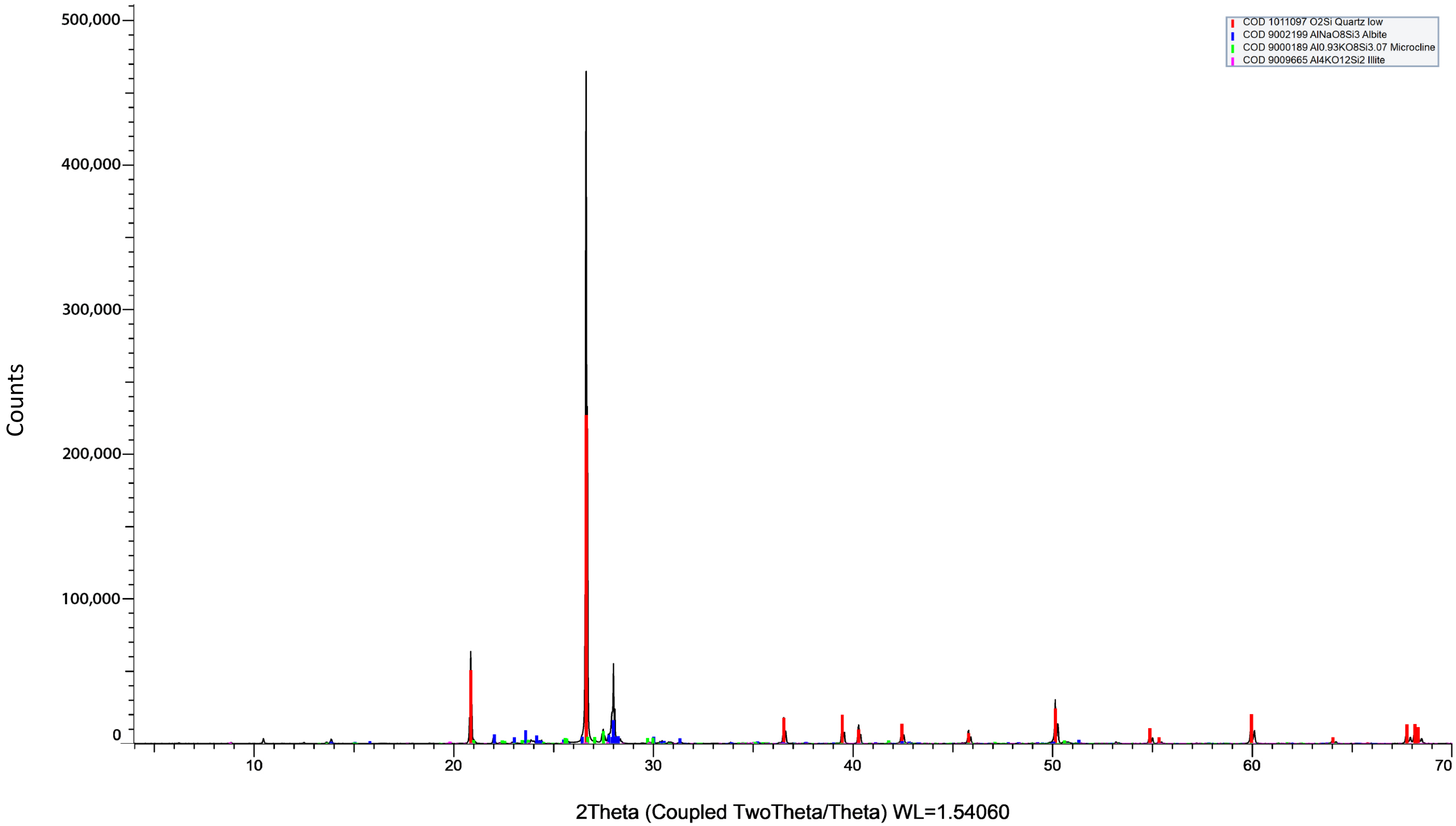


Figure A-II-6. XRD phase diagram of sand sample no. 5a from the northern Brampton (Riverdale Ridge) Dunes in southwestern Sargent County, North Dakota.

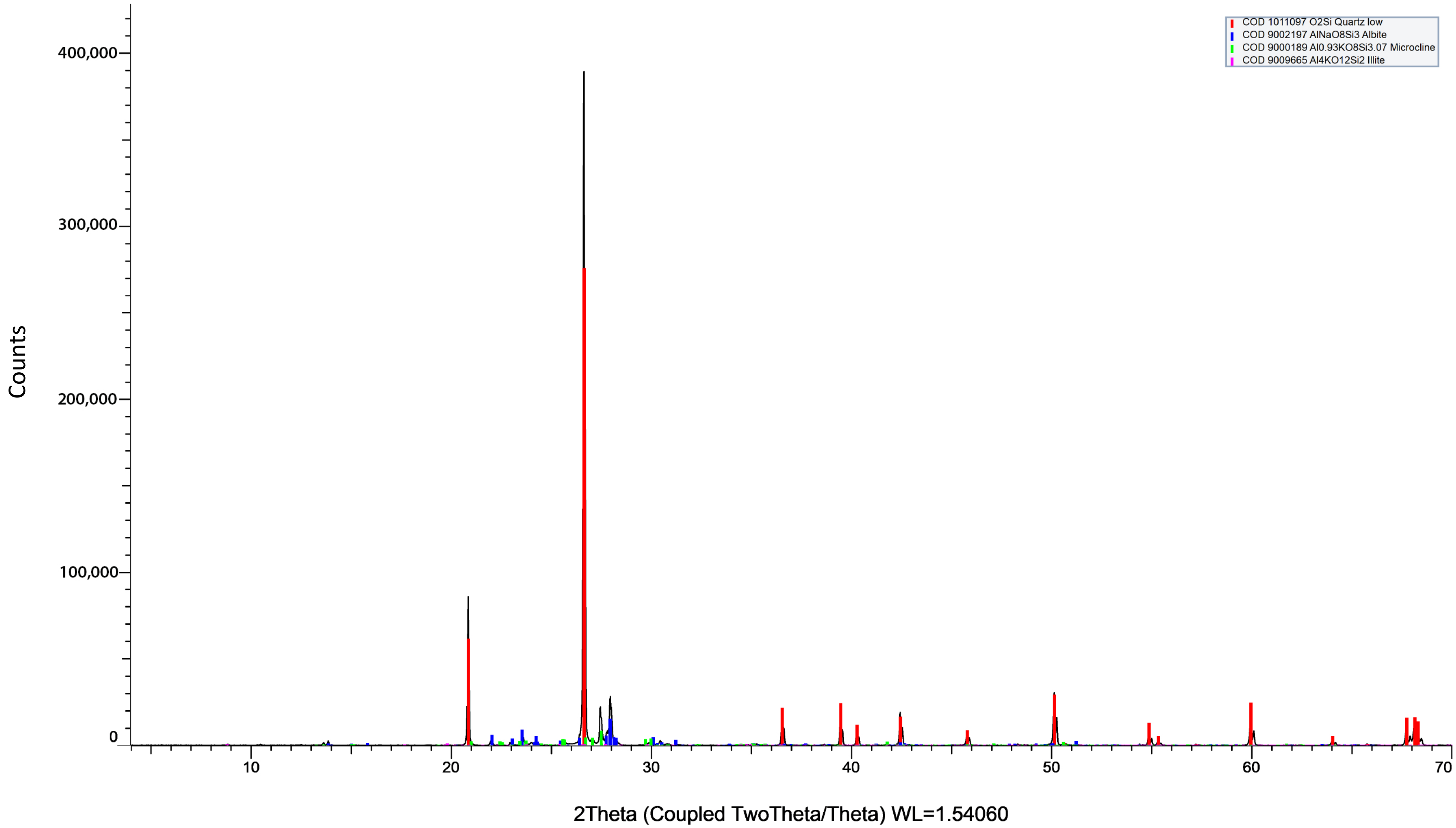


Figure A-II-7. XRD phase diagram of sand sample no. 5b from the northern Brampton (Riverdale Ridge) Dunes in southwestern Sargent County, North Dakota.

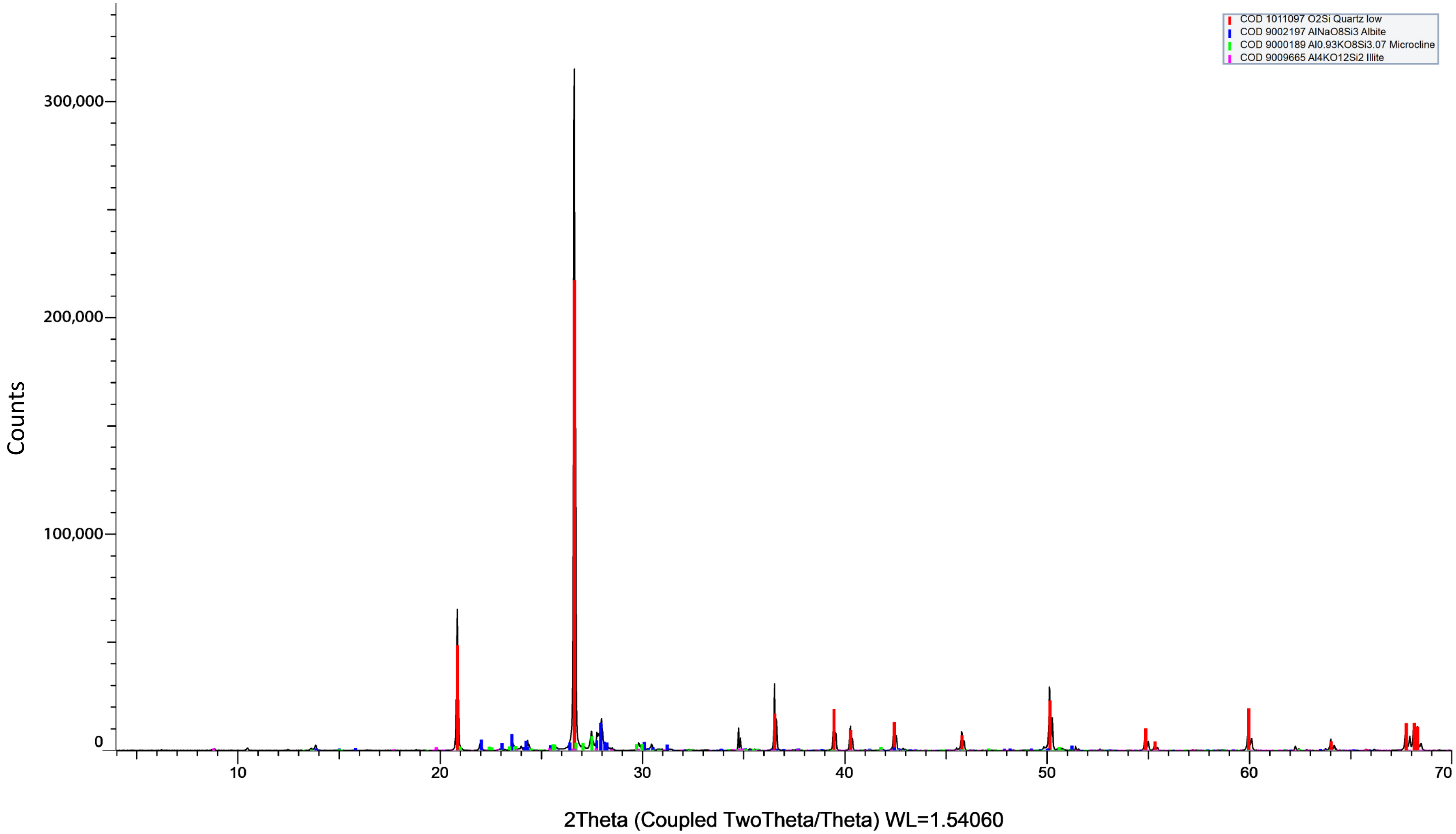


Figure A-II-8. XRD phase diagram of sand sample no. 6 from the southern Brampton (Riverdale Ridge) Dunes in southwestern Sargent County, North Dakota.

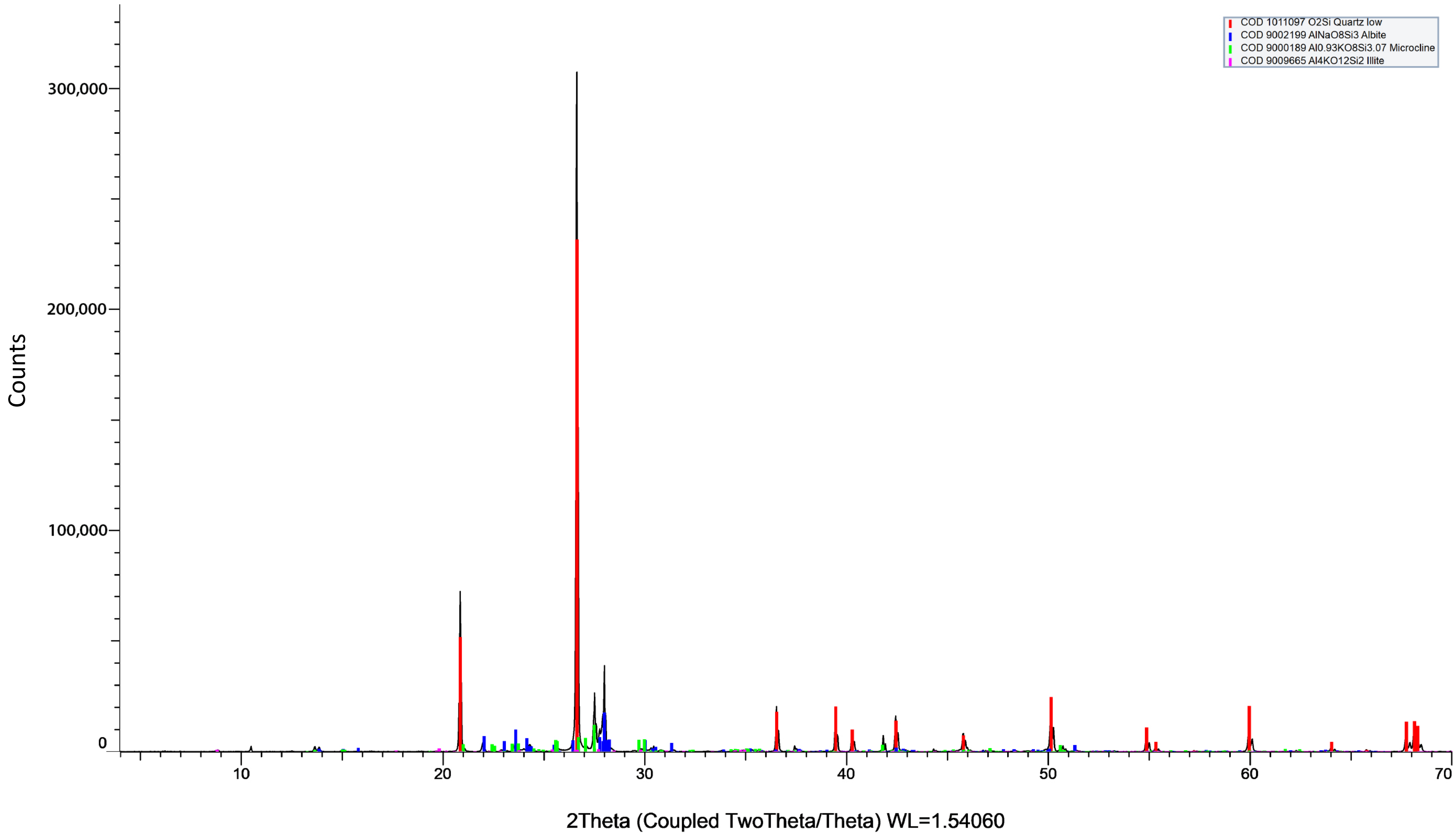


Figure A-II-9. XRD phase diagram of sand sample no. 7 from the LaMoure Southeast Sands in southeastern LaMoure County, North Dakota.

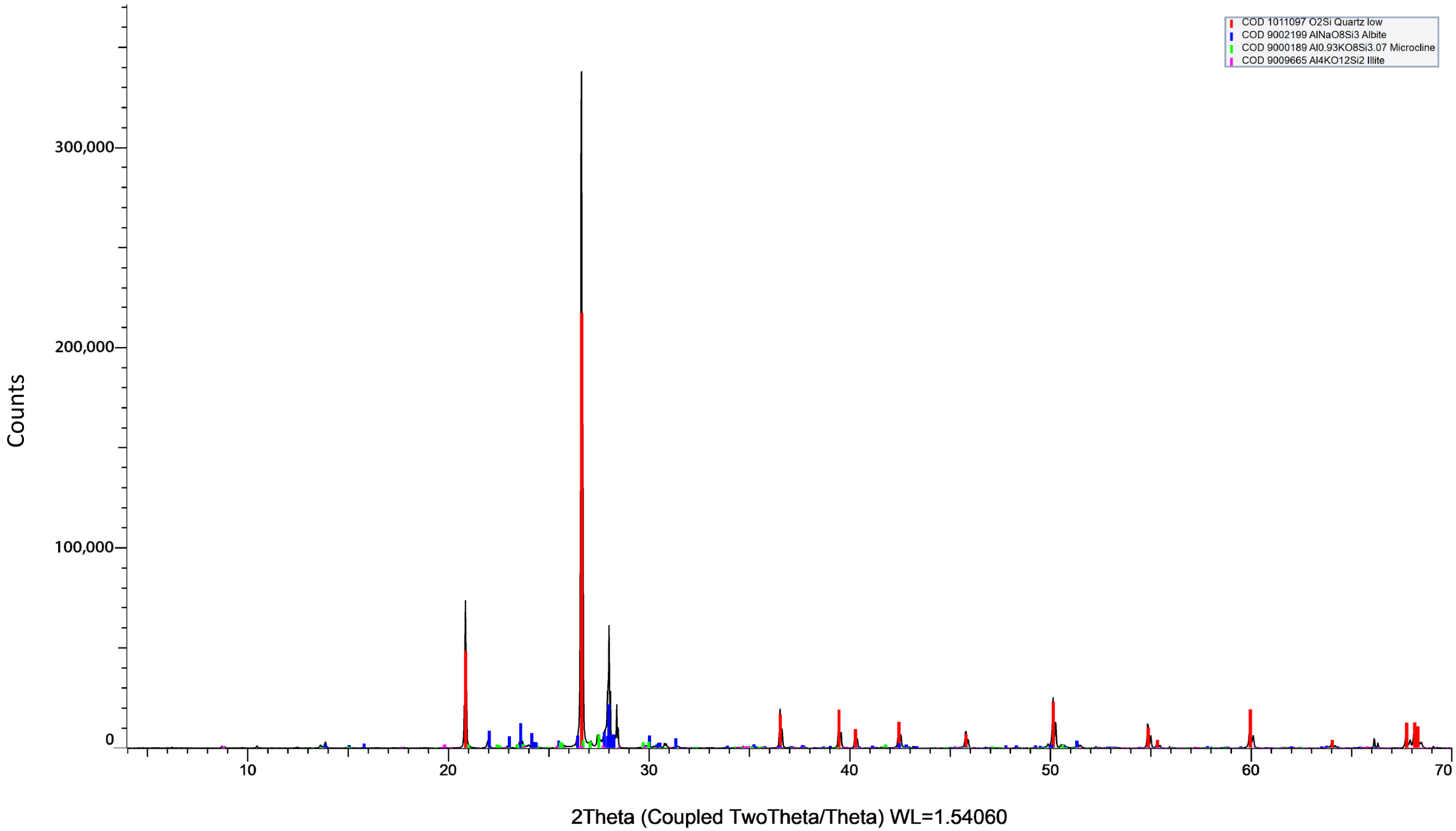


Figure A-II-10. XRD phase diagram of sand sample no. 8 from the Edinburg Sands in north-central Walsh County, North Dakota.

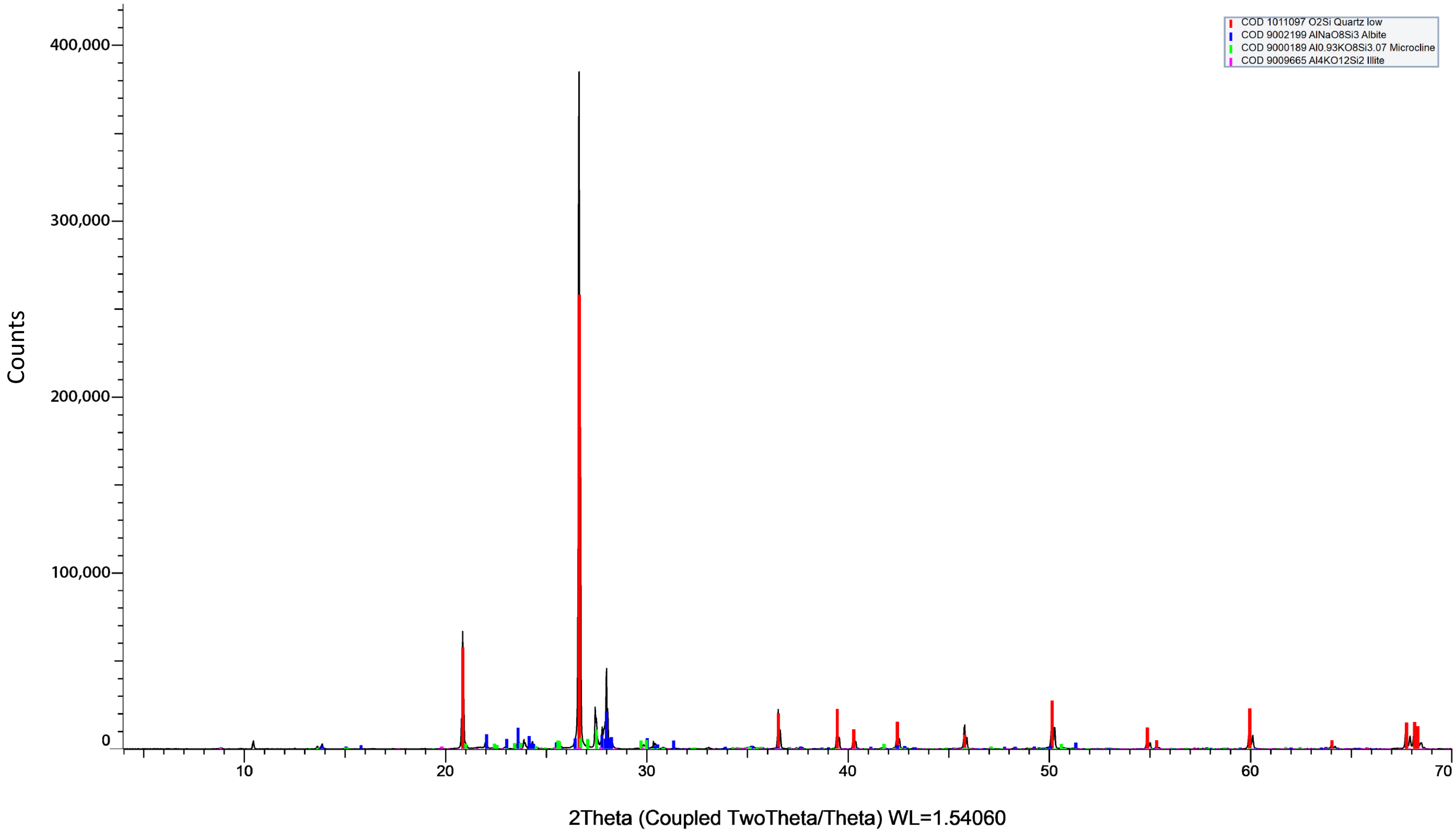


Figure A-II-11. XRD phase diagram of sand sample no. 9 from the Larimore Sands in west-central Grand Forks County, North Dakota.

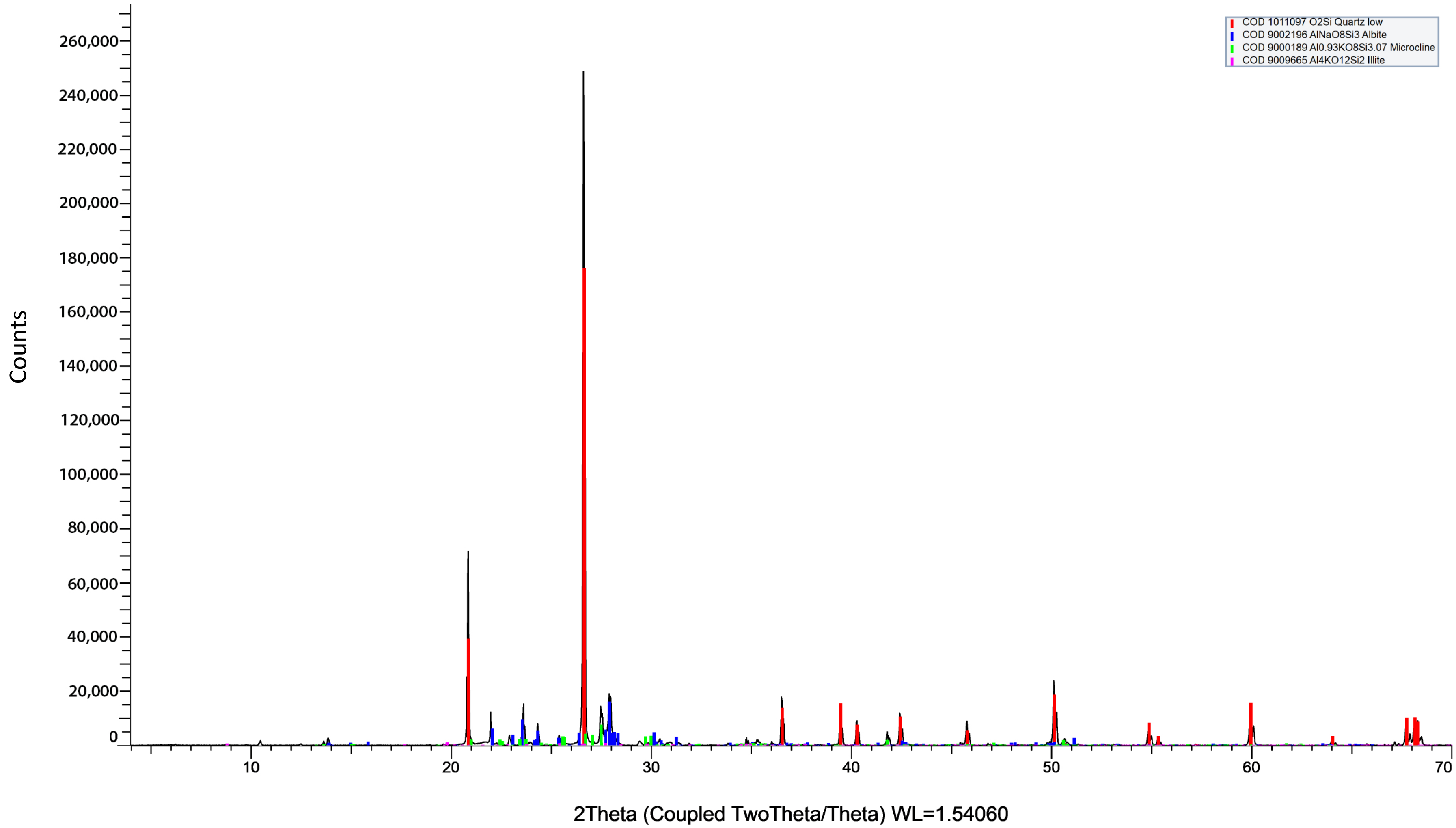


Figure A-II-12. XRD phase diagram of sand sample no. 10a from the northern Hankinson Dunes in south-central Richland County, North Dakota.

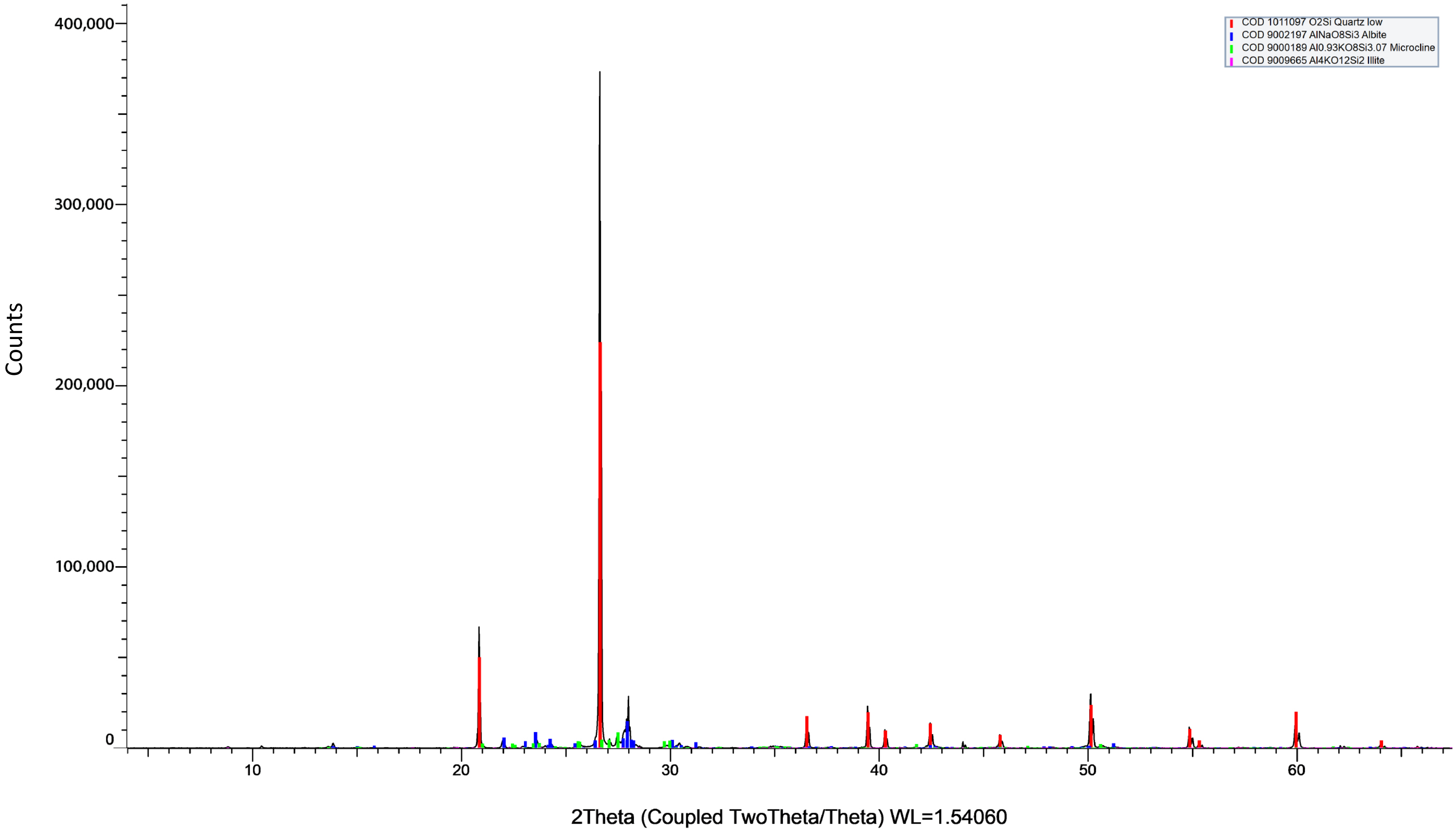


Figure A-II-13. XRD phase diagram of sand sample no. 10b from the northern Hankinson Dunes in south-central Richland County, North Dakota.

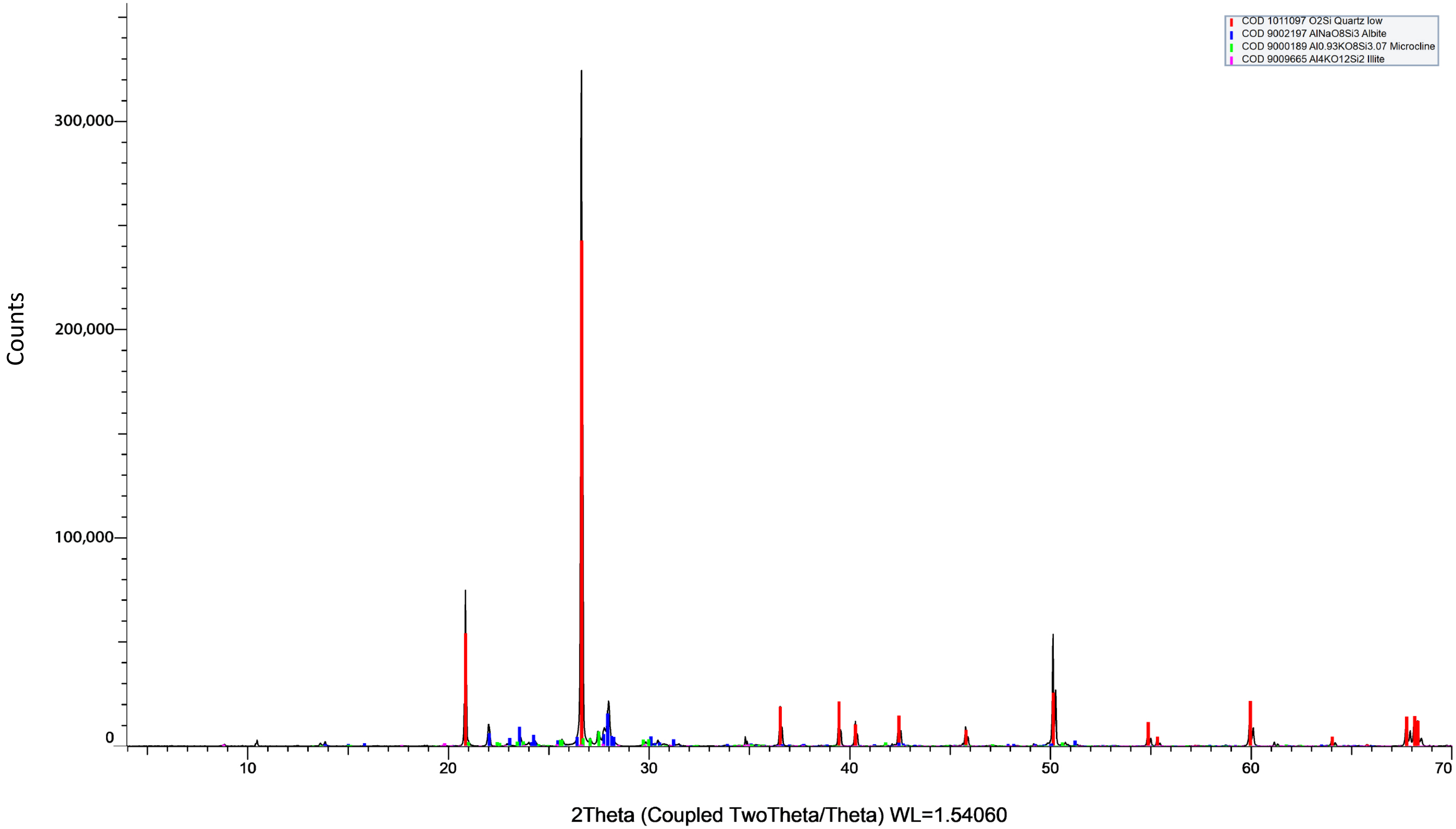


Figure A-II-14. XRD phase diagram of sand sample no. 11a from the northern Sheyenne Dunes in northwestern Richland County, North Dakota.

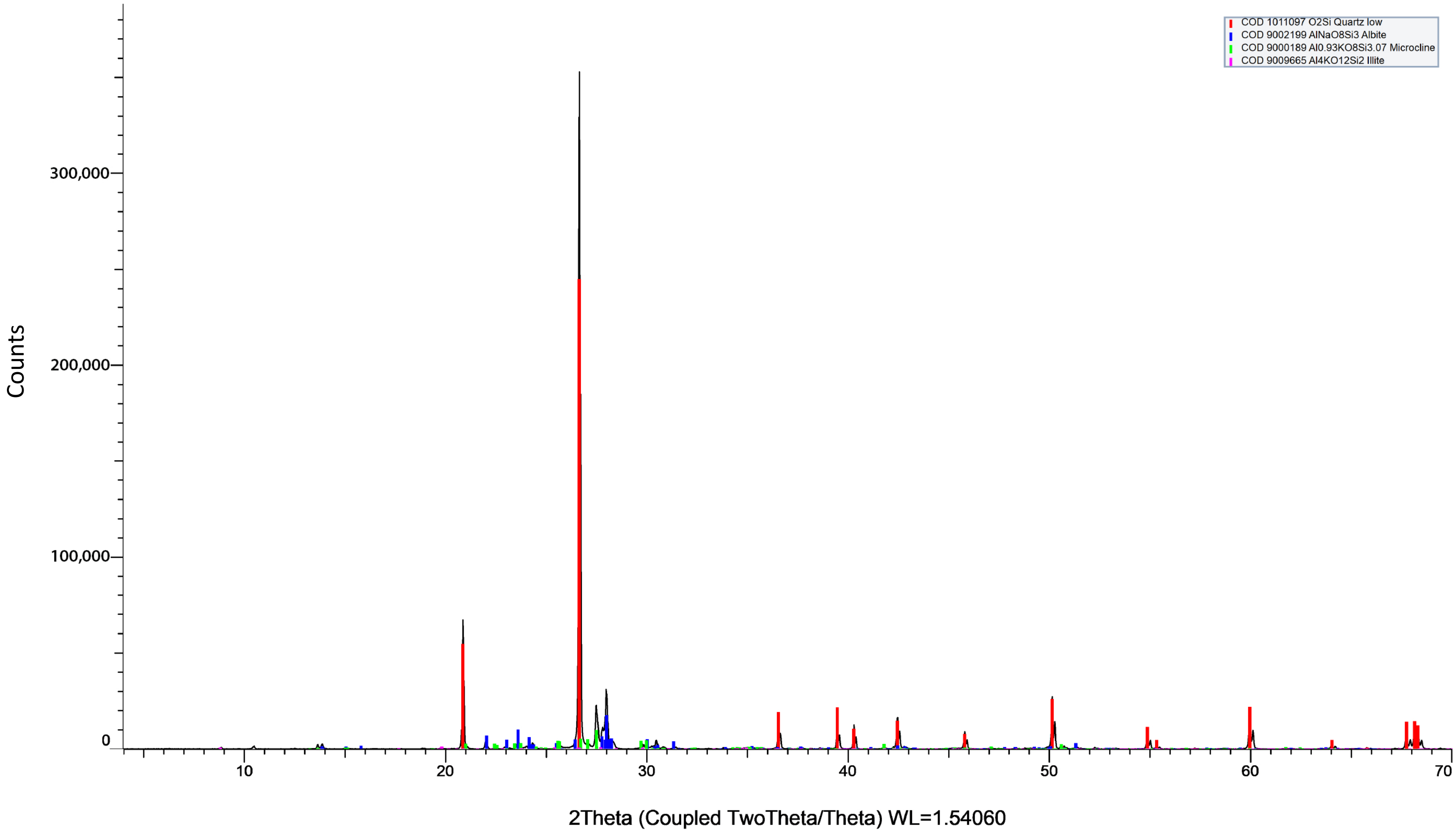
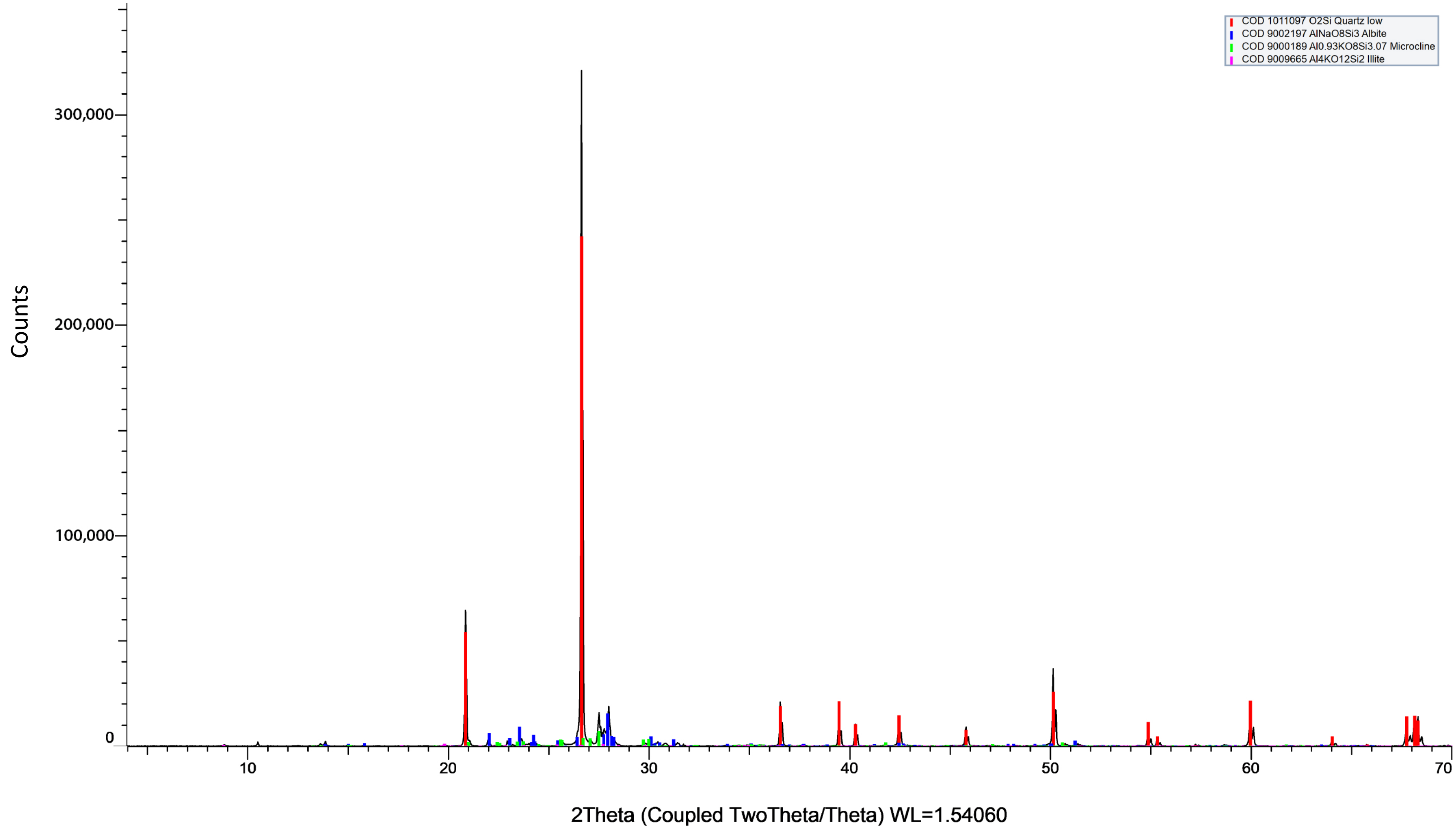


Figure A-II-15. **XRD phase diagram of sand sample no. 11b from the northern Sheyenne Dunes in northwestern Richland County, North Dakota.**



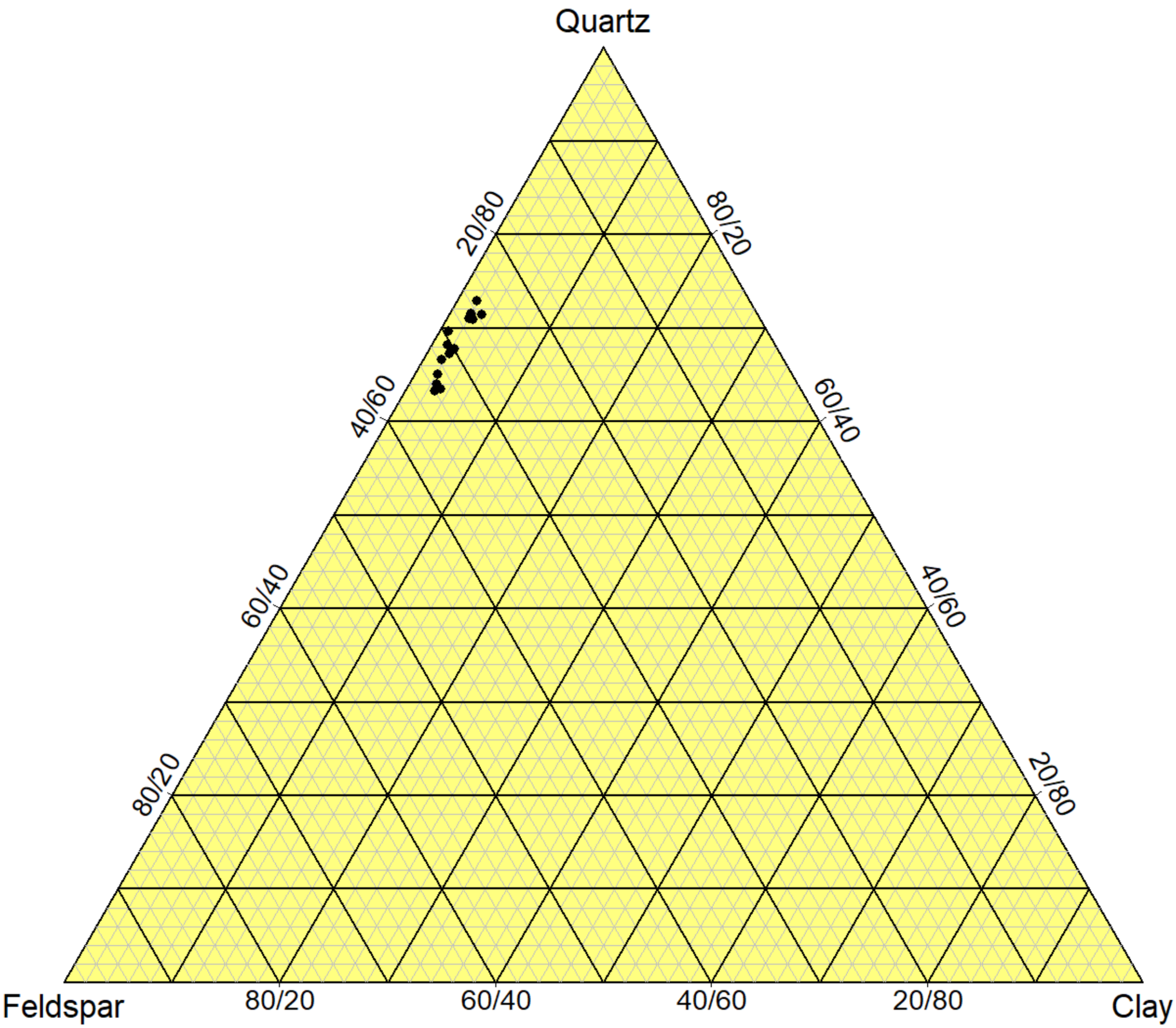


Figure A-II-16. Ternary diagram of processed (washed and sized) sand mineralogy (weight %) from X-ray diffraction (XRD) analysis of windblown sand deposits in south-central North Dakota. The sands are quartz dominated with moderate amounts of feldspars and little clays. No carbonates were detected in these samples. Like other windblown deposits found in North Dakota, the close grouping in this graph illustrates how similar the mineralogy of these deposits are to one another.

Appendix III. Mineralogy of a Bulk Windblown Sand Sample from the Pembina Dunes in Northeastern North Dakota by X-ray diffraction (XRD) Analysis.

Introduction

XRD analysis of a sample of bulk (unwashed and unsized) windblown sand from the Pembina Dunes in northeastern North Dakota was completed in 2020 as a part of 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. As a part of this investigation, samples were submitted to Stim-Lab, Inc. in Duncan, Oklahoma for analysis. This sample was obtained from the lower portion of a high-relief dune exposure in the northern Pembina Dunes in northwestern Pembina County (T. 161 N., R. 56 W., Sec. 15., SE1/4).

XRD Methodology

The testing values reported in Table A-III-1 included in this appendix represent the identified mineralogical phases contained within this bulk sand sample as reported in weight %. It should be noted that this sand sample was 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
Pembina Dunes	70	12	13	25	--	--	--	1	1	*tr.*	*tr.*	2	3	--	--	--

** 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.