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

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Abstract

Sampling and testing of windblown sand deposits in north-central North Dakota was completed in 2019 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 28 samples from 22 locations within the Denbigh Dunes. These dunes are the windblown accumulate of glaciolacustrine sand deposited in the former Glacial Lake Souris. Selected sand size classes (typically 40/70 and 70/140) were tested from low and high-relief dune fields. Testing results indicate these sands are consistently well sorted, medium to very-fine grained, with crush resistance ranging from 4,000 to 7,000 psi (4K to 7K). Acid solubility averaged 6.3% and turbidity 28% 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 are within the desired ranges for proppant use and average 0.6 for roundness and 0.8 for sphericity. Mineralogically, no carbonates were found in the washed and sized samples which averaged 76% quartz, with 22% felspars (albite and microcline), and 1.1% clays (illite). Overall, these windblown sand deposits appear suitable for use as proppant given the current industry requirements.

Acknowledgements

The authors 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 within Trust Lands. Sand testing services (proppant analysis) was provided by Lonquist Field Services in College Station, Texas. Cartographic support was provided by Mr. Navin Thapa, GIS Specialist with the North Dakota Geological Survey. SEM images of individual quartz sand grains were produced by Rocky Mountain Laboratories in Golden, Colorado. Drone photography, bulk sand photomicrography, and field sampling support on several locations was provided by Mr. Levi Moxness, Geologist with the NDGS. Additional review and comments were provided by Mr. Jeff Person and Mr. Chris Maike, also of the NDGS.

Author's Note

Recently the oil and gas industry has relaxed proppant testing specifications in part of the U.S. in favor of more regional or local proppant sand source utilization. In-basin proppant sand is currently being produced in the Denbigh Dunes just south of Denbigh, North Dakota and appears suitable for continued use. This report characterizes the eolian sand that is found in the Denbigh area, and across McHenry County, providing an expanded view of the possibilities for continued development of this sand resource in north-central North Dakota.

Cover photo: A high-relief dune in the southern Denbigh Dunes south of Towner, North Dakota. Dunes like this are common throughout this area and occur as parts of larger coalesced dune fields throughout McHenry County. These dunes typically reach heights of up to 60 feet (18.3m).

TABLE OF CONTENTS

TABLE OF CONTENTS (Contd.)

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

APPENDICES

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). Sampling and testing efforts were concentrated in the Denbigh Dunes because they are the largest expanse of eolian sand in North Dakota and are the closest to the heart of current oil development activity.

Sand samples from the Denbigh Dunes in McHenry County were collected during the 2019 field season and submitted to Lonquist Field Services in College Station, Texas, for proppant testing and characterization (Figure 1). Bulk sand samples were collected in five-gallon buckets at 22 locations (DD-1 through DD-22) distributed across McHenry County (Figure 2). Samples were collected both 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 performed on the most abundant size classes, as determined by sieve analysis, which typically fell into the 40/70 and 70/140 size classes. Since several of the samples collected showed similar size class percentages within these two dominant size classes, both size classes were tested and evaluated in order to provide more useful information to industry.

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) was preferred, which over time has changed to the finer sand size classes in the 40/70 and 70/140 ranges. As testing progressed, a 50/140 sand was also tested from location DD-21 in order to provide a representative set of testing results on this size class.

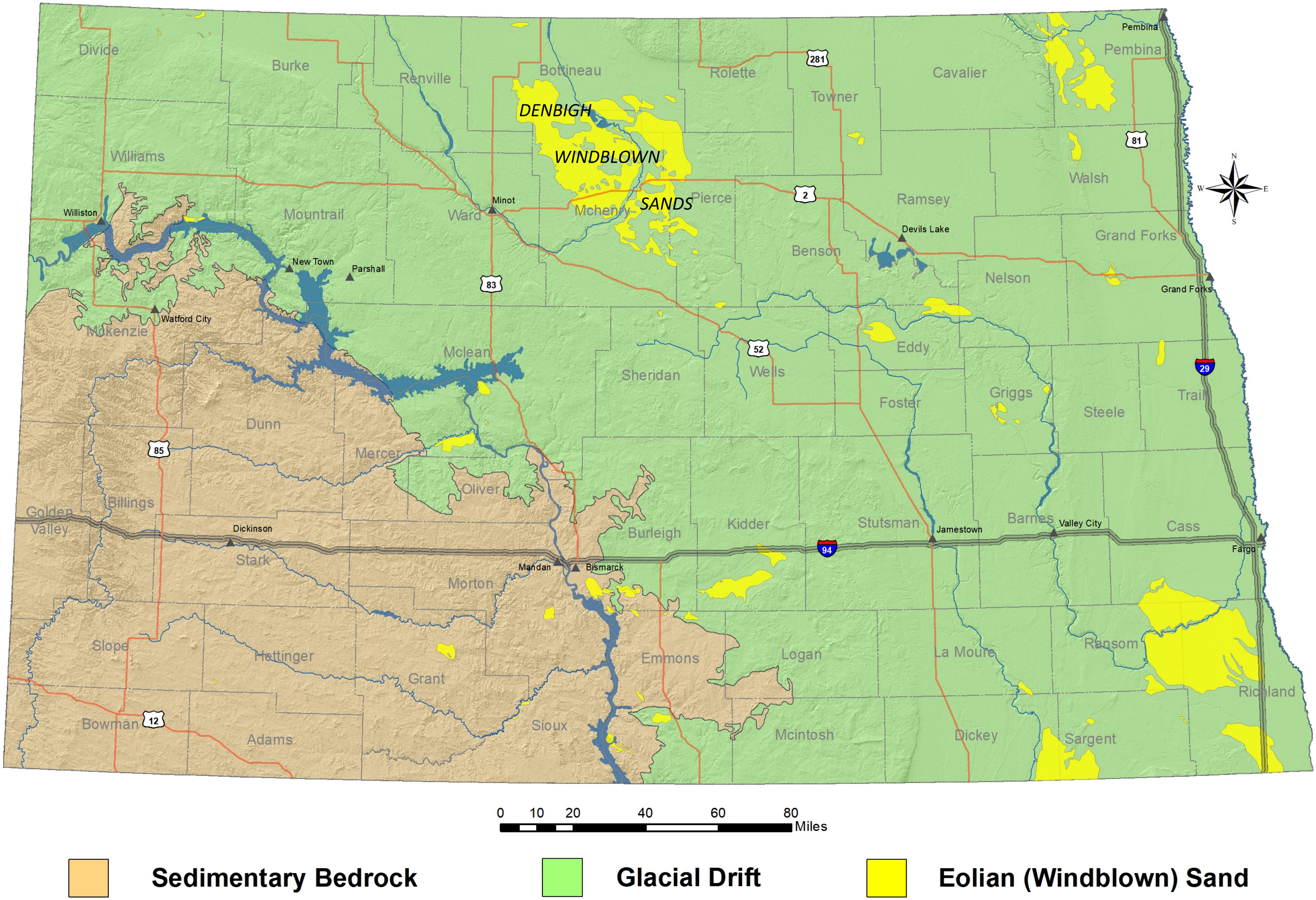

Figure 1. Location of windblown sand in North Dakota. The Denbigh sand deposits cover over 989 square miles making it the largest accumulation of windblown sand in North Dakota.

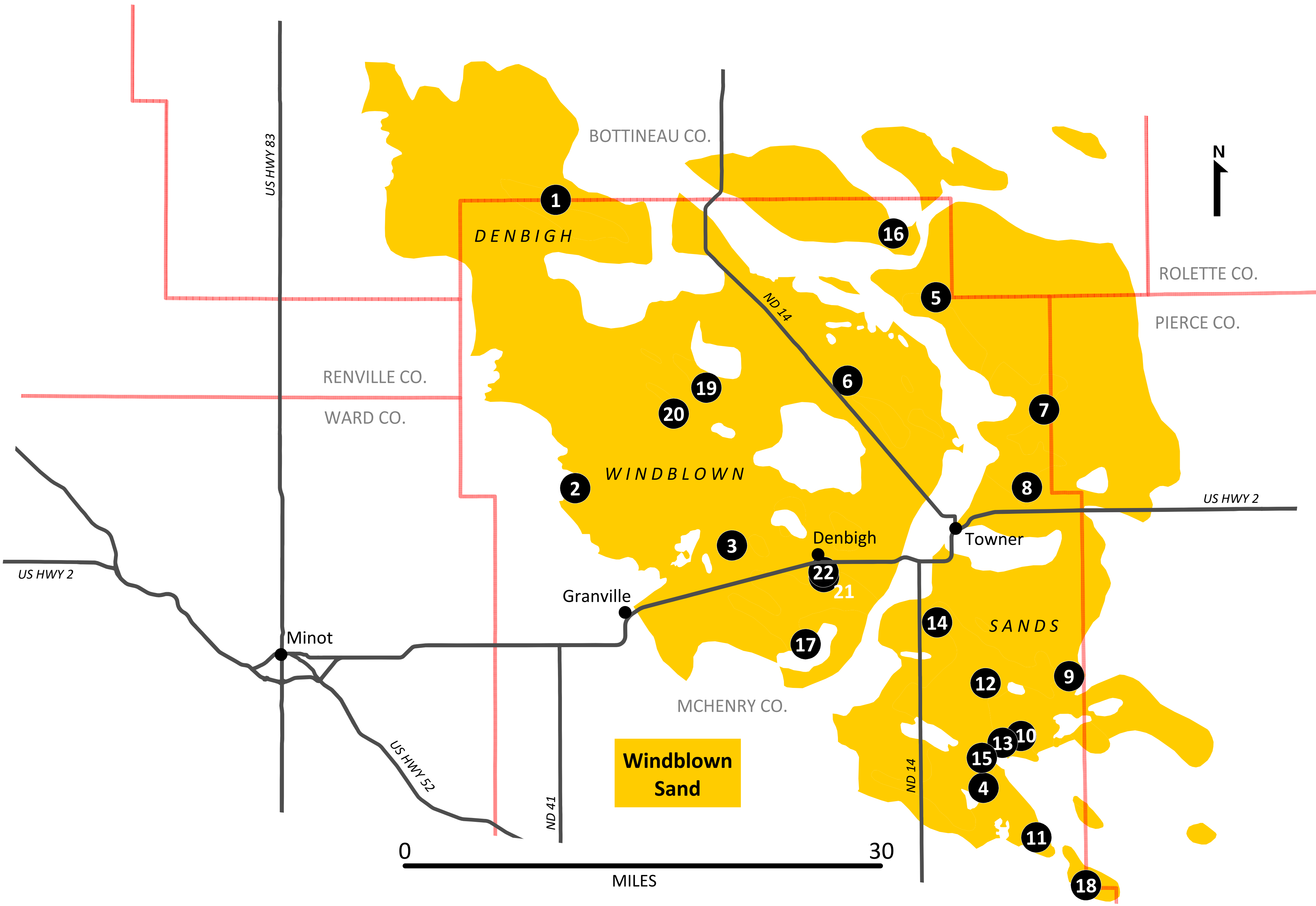

Figure 2. Location of samples collected from the Denbigh windblown sands in 2019 for proppant evaluation.

Table 1. Sample Location Summary

Sample No.	Eolian Sand Area	County	Location (PLSS)	Description	Field Acid Reactivity (10% HCl)
DD-1*	Denbigh Dunes	Bottineau	160-80-36-SE	Low Dunes, Ground Exposure	NR
DD-2*	Denbigh Dunes	McHenry	157-79-31-SE	Low Dunes, Ground Exposure	NR
DD-3*	Denbigh Dunes	McHenry	156-78-16-SE	Low Dunes, Ground Exposure	NR
DD-4*	Denbigh Dunes	McHenry	154-76-36-SE	High Dunes, Dune Exposure	NR
DD-5*	Denbigh Dunes	McHenry	159-76-36-SW	Low Dunes, Ground Exposure	NR
DD-6*	Denbigh Dunes	McHenry	158-77-36-NE	Low Dunes, Ground Exposure	NR
DD-7*	Denbigh Dunes	McHenry	157-75-1-SE	Low Dunes, Ground Exposure	NR
DD-8*	Denbigh Dunes	McHenry	157-75-35-SW	Low Dunes, Ground Exposure	NR
DD-9*	Denbigh Dunes	McHenry	155-75-36-NW	High Dunes, Dune Exposure	NR
DD-10*	Denbigh Dunes	McHenry	154-75-16-SW	High Dunes, Dune Exposure	NR
DD-11*	Denbigh Dunes	McHenry	153-75-16-SE	Low Dunes, Ground Exposure	NR
DD-12*	Denbigh Dunes	McHenry	155-76-36-NE	High Dunes, Dune Exposure	NR
DD-13	Denbigh Dunes	McHenry	154-75-19-NE	High Dunes, Dune Exposure	NR
DD-14	Denbigh Dunes	McHenry	155-76-10-SW	High Dunes, Dune Exposure	NR
DD-15	Denbigh Dunes	McHenry	154-76-24-SE	High Dunes, Dune Exposure	NR
DD-16*	Denbigh Dunes	McHenry	159-76-16-NW	Low Dunes, Ground Exposure	NR
DD-17	Denbigh Dunes	McHenry	155-77-17-SW	High Dunes, Dune Exposure	NR
DD-18*	Denbigh Dunes	McHenry	153-75-36-SE	Low Dunes, Ground Exposure	NR
DD-19	Denbigh Dunes	McHenry	158-78-33-NE	High Dunes, Dune Exposure	NR
DD-20	Denbigh Dunes	McHenry	157-78-5-SW	Low Dunes, Ground Exposure	NR
DD-21**	Denbigh Dunes	McHenry	156-77-28-SW	High Dunes, Dune Exposure	NR
DD-22**	Denbigh Dunes	McHenry	156-77-28-SW	High Dunes, Dune Exposure	NR

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

*** = Sample locations on BLM Surface Minerals Land.*

NR = Non-Reactive.

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).

It is worth noting that prior to the recent proppant characterization studies, Lemke (1960), Bluemle (1982), and Lord (1988) mapped windblown deposits in north-central North Dakota. Much of the investigative direction of this study was provided by these earlier works.

WINDBLOWN SAND IN NORTH-CENTRAL NORTH DAKOTA

Windblown sand deposits in north-central North Dakota are extensive, occurring across the northern two-thirds of McHenry County and extending into southern Bottineau and western Pierce counties (Figure 1). The Denbigh sand deposits cover an area of approximately 1,000 square miles (2,590 km) and are located 25 miles northeast of Minot. The sands were originally deposited in the former Glacial Lake Souris, which extended from just north of Bottineau County into southeastern Saskatchewan and southwestern Manitoba and down into southeastern McHenry and southwestern Pierce counties. The sands were deposited as proglacial lake deposits prior to the eventual retreat of the lake likely around 7,000 years ago (Bluemle, 1982). Subsequent eolian processes transported the finer sand fractions across the former lake bottom into localized dune fields (Plate I). The sands are distributed into two major settings, 1) as high-relief dunes, with relief commonly ranging from 10 to 60 feet (3 to 18 m), in coalesced dune fields which encompass approximately 30% of the area occupied by eolian sand, and 2) as gently rolling tabular sheet sands with areas of occasional low dunes with relief of up to ten feet (3 m). All the windblown sands in this area tend to be under vegetative cover (crop lands, grasses, shrubs, and trees) with only the occasional blowout or dune face exposing the underlying sand. Quaking aspen are common in the high-relief dune fields and tend to be some of the first types of vegetation to take hold in these previously open sandy areas (Gaither, 2020).

High-Relief Dunes

There are as many as 81 distinct high-relief dune fields mappable throughout the area which cover an estimated 300 square miles (483 km). The high-relief dune fields tend to be distributed within the central three-fourths of the area and are generally elongated from the northwest to the southeast (Plate I), in line with the prominent paleo-wind direction. The relief on these dunes tend to decrease with an overall decrease in the size of the dune field. Half of the 22 samples collected as a part of this investigation, were from high-relief dunes.

Low-Relief Dunes

The area in between the high-relief dune fields is covered with gently rolling to flat tabular sheet sands that contain occasional low-relief dunes. These low-relief dunes cover approximately 700 square miles (1,813 km). To an observer on the ground the distance between high-relief dune fields can appear quite large, making these lower-relief areas appear somewhat featureless and expansive. Eleven of the 22 samples collected for this investigation were collected from areas with low-relief dunes (Table I).

Dunes on Trust Lands

There is a total of 50 tracts of Trust Lands within the areal extent of the Denbigh deposits that total 32.3 square miles (83.6 km^2). Most of the Trust Lands are in one-square mile sections (640 acres) that are evenly distributed over the southern third of the area. The northeastern and northern portions of the Denbigh deposits have little Trust Land within their extent. The Cities of Towner and Denbigh are located along U.S. HWY 2 in the central portion of the Denbigh deposits. Fourteen of the 22 samples were collected from Trust Lands (Plate I).

Groundwater Conditions

The water-table is shallow throughout the area and can be found within 3 to 11 feet of land surface outside the high-relief dune fields (NDSWC, 2020). Groundwater is shallow across the area and is directly influenced by local shallow surface hydrologic features such as rivers, lakes, and ponds.

SAND SAMPLE LOCATIONS

Bulk samples of windblown sand were collected in five-gallon buckets from selected locations across the Denbigh deposits in 2019 and were submitted for additional proppant testing (Figure 3). None of the samples collected reacted to dilute (10%) HCL in the field suggesting sand devoid of carbonate minerals.

Sample DD-1

Sample DD-1 was collected from a hand-shovel pit excavated into a low-relief dune on the northwestern (upwind) end of the Denbigh Windblown Sands in southern Bottineau County in the SE1/4 of Section 36, T. 160 N., R. 80 W. (Figure 4). This sample location is located approximately five miles southwest of Newburg on North Dakota Trust Lands.

Sample DD-2

Sample DD-2 was collected from a hand-shovel pit excavated into a low-relief dune on the western margin of the Denbigh Windblown Sands in western McHenry County in the SE1/4 of Section 31, T. 157 N., R. 79 W. (Figure 5). This sample location is located approximately 6.5 miles east of Deering and eight miles northwest of Granville on North Dakota Trust Lands.

Sample DD-3

Sample DD-3 was collected from a hand-shovel pit excavated into a low-relief dune in the west-central portion of the Denbigh Windblown Sands in central McHenry County in the SE1/4 of Section 16, T. 156 N., R. 78 W. (Figure 6). This sample location is located approximately 2.5 miles north of Riga and 5.5 miles west of Denbigh on North Dakota Trust Lands.

Sample DD-4

Sample DD-4 was collected from a hand-shovel pit in a surface exposure along a high-relief dune on the southern end of a larger coalesced dune field in the southeastern portion of the Denbigh Windblown Sands in central McHenry County in the SE1/4 of Section 36, T. 154 N., R. 76 W. (Figure 7). This sample location is located approximately 15.5 mile south of Towner and 11 miles east of Karlsruhe on North Dakota Trust Lands.

Sample DD-5

Sample DD-5 was collected from a hand-shovel pit excavated into a low-relief dune on the northern portion of the Denbigh Windblown Sands in northeastern McHenry County in the SW1/4 of Section 36, T. 159 N., R. 76 W. (Figure 8). This sample location is located approximately nine miles northeast of Bantry and seven miles southwest of Willow City on North Dakota Trust Lands.

Figure 3. View to the north of the author field sampling from a vegetation-stabilized high-relief dune (DD-4 this report) south of Towner, North Dakota (T.154N.,R.76W., Sec.36, SE1/4).

Figure 4. Drone image (view to the northeast) across low-relief dunes located on North Dakota Trust Lands in southwestern Bottineau County (T.160N., R.80W., Sec.36, SE1/4). Sample No. DD-1 was collected from this location.

Figure 5. Drone image (view to the northeast) across low-relief dunes located on North Dakota Trust Lands in northeastern McHenry County (T.157N., R.79W., Sec.31, SE1/4). Sample No. DD-2 was collected from this location.

Figure 6. Drone image (view to the southwest) across heavily wooded high-relief dunes in central McHenry County (T.156N., R.78W., Sec.16, SE1/4). Sample No. DD-3 was collected from an area of low-relief dunes just northeast of this area on North Dakota Trust Lands.

Figure 7. Drone image (view to the west) of high-relief dunes on North Dakota Trust Lands located south of Towner, North Dakota (T.154N.,R.76W., Sec.36, SE1/4). Sample No. DD-4 was collected at this location.

Figure 8. View to the east of low-relief dunes on North Dakota Trust Lands located between Upham and Willow City, North Dakota (T.159N.,R.76W., Sec.36, SW1/4). Sample No. DD-5 was collected at this location.

Sample DD-6

Sample DD-6 was collected from a hand-shovel pit excavated into a low-relief dune on the central portion of the Denbigh Windblown Sands in north-central McHenry County in the NE1/4 of Section 36, T. 158 N., R. 77 W. (Figure 9). This sample location is located approximately ten miles northwest of Towner and 3.5 miles southeast of Bantry on North Dakota Trust Lands.

Sample DD-7

Sample DD-7 was collected from a hand-shovel pit excavated into a low-relief dune on the northeastern portion of the Denbigh Windblown Sands in northeastern McHenry County in the SE1/4 of Section 1, T. 157 N., R. 75 W. (Figure 10). This sample location is located approximately eight miles northeast of Towner, 2.5 miles northwest of Horseshoe Lake, on North Dakota Trust Lands.

Sample DD-8

Sample DD-8 was collected from a hand-shovel pit excavated into a low-relief dune on the eastern portion of the Denbigh Windblown Sands in eastern McHenry County in the SW1/4 of Section 35, T. 157 N., R. 35 W. (Figure 11). This sample location is located approximately five miles northeast of Towner and three miles northwest of Berwick, on North Dakota Trust Lands three miles north of US Highway 2.

Sample DD-9

Sample DD-9 was collected from a hand-shovel pit in a dune exposure on a high-relief dune on the southeastern portion of the Denbigh Windblown Sands in southeastern McHenry County in the NW1/4 of Section 36, T. 155 N., R. 75 W. (Figure 12). This sample location is located approximately 12 miles southeast of Towner on North Dakota Trust Lands.

Sample DD-10

Sample DD-10 was collected from a hand-shovel pit in a dune exposure on a high-relief dune on the southeastern portion of the Denbigh Windblown Sands in southeastern McHenry County in the SW1/4 of Section 16, T. 154 N., R. 75 W. (Figure 13). This sample location is located approximately 13 miles south and east of Towner on North Dakota Trust Lands.

Sample DD-11

Sample DD-11 was collected from a hand-shovel pit excavated into a low-relief dune on the southeastern portion of the Denbigh Windblown Sands in southeastern McHenry County in the SE1/4 of Section 16, T. 153 N., R. 75 W. (Figure 14). This sample location is located approximately 20 miles south of Towner and 15 miles east of Karlsruhe on North Dakota Trust Lands.

Figure 9. View to the south of low-relief dunes on North Dakota Trust Lands 3.5 miles southeast of Bantry, North Dakota (T.158N.,R.77W., Sec.36, NE1/4). Sample No. DD-6 was collected at this location. Survey drone pilot Levi Moxness (at back of truck) operates the drone while the author is serving as a spotter.

Figure 10. View to the northeast of low-relief dunes on North Dakota Trust Lands nine miles northeast of Towner, North Dakota (T.157N.,R.75W., Sec.1, SE1/4). Sample No. DD-7 was collected at this location.

Figure 11. View to the northeast of low-relief dunes on North Dakota Trust Lands located nine miles northeast of Towner, North Dakota (T.157N.,R.75W., Sec.35, SE1/4). Sample No. DD-8 was collected at this location.

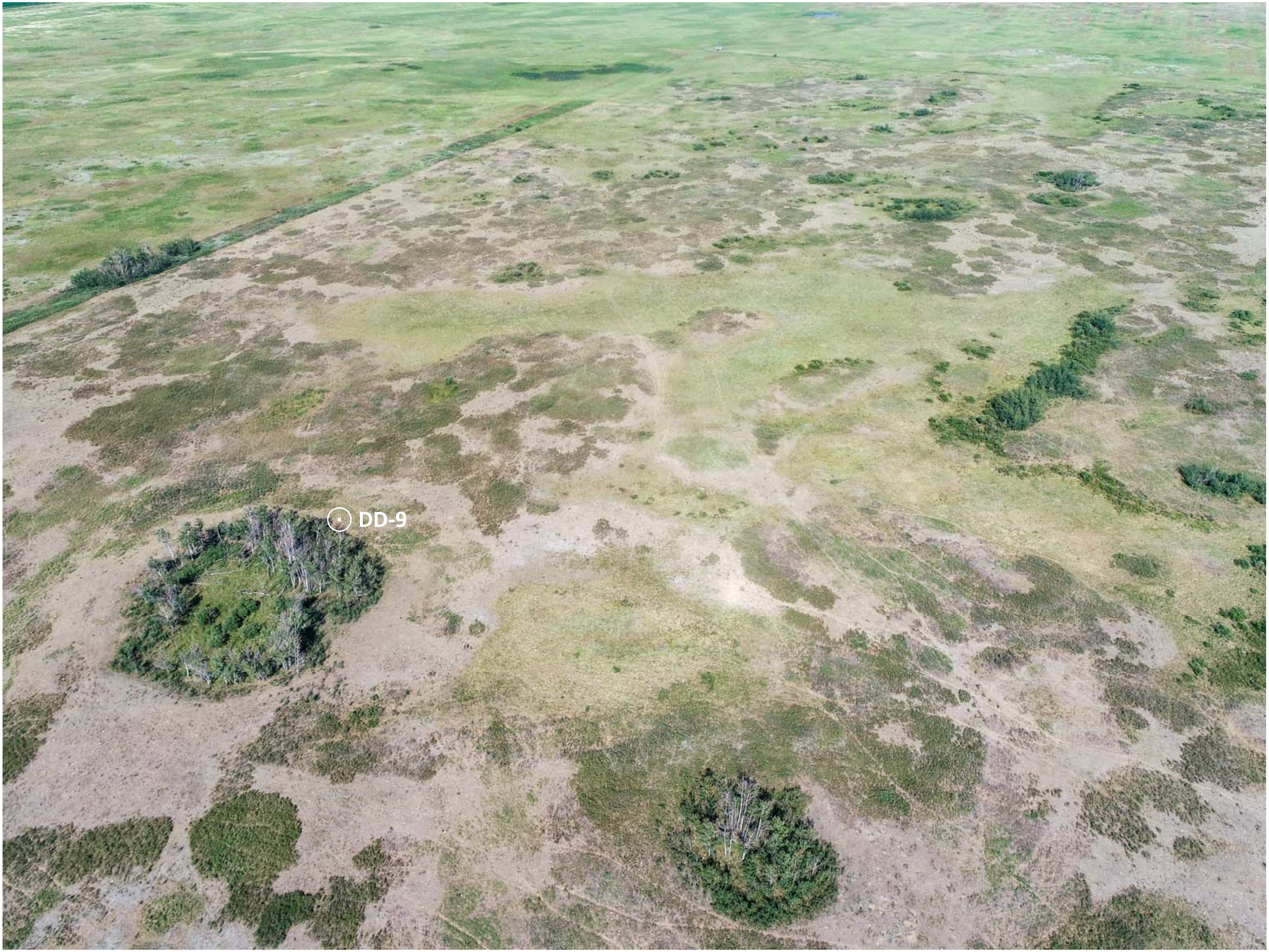

Figure 12. View to the northeast of high-relief dunes on North Dakota Trust Lands twelve miles northeast of Towner, North Dakota (T.155N.,R.75W., Sec.36, NW1/4). Sample No. DD-9 was collected at this location.

Figure 13. View to the southeast of high-relief dunes on North Dakota Trust Lands in southeastern McHenry County (T.154N., R.75W., Sec.16, SW1/4). Sample No. DD-10 was collected from the dune exposure at the location of the green bucket and shovel.

Figure 14. View to the south along low-relief dunes on North Dakota Trust Lands in southeastern McHenry County (T.153N., R.75W., Sec.10, SE1/4). Sample No. DD-11 was collected at this location.

Sample DD-12

Sample DD-12 was collected from a hand-shovel pit in a dune exposure on a high-relief dune on the southeastern portion of the Denbigh Windblown Sands in southeastern McHenry County in the NE1/4 of Section 36, T. 155 N., R. 76 W. (Figure 15). This sample location is located approximately 10 miles south of Towner on North Dakota Trust Lands.

Sample DD-13

Sample DD-13 was collected from a hand-shovel pit from a dune exposure on a high-relief dune on the southeastern portion of the Denbigh Windblown Sands in southeastern McHenry County in the NE1/4 of Section 19, T. 154 N., R. 75 W. (Figure 16). This sample location is located approximately 14 miles south of Towner.

Sample DD-14

Sample DD-14 was collected from a hand-shovel pit from a dune exposure on a high-relief dune on the southeastern portion of the Denbigh Windblown Sands in southeastern McHenry County in the SW1/4 of Section 10, T. 155 N., R. 76 W. (Figure 17). This sample location is located approximately six miles south of Towner.

Sample DD-15

Sample DD-15 was collected from a hand-shovel pit from a dune exposure on a high-relief dune on the southwestern arm of a larger dune field surrounding Bald Butte to the west and north in southeastern McHenry County in the SE1/4 of Section 24, T. 154 N., R. 76 W. (Figure 18). This sample location is located approximately 14 miles south of Towner and 12 miles northeast of Karlsruhe.

Sample DD-16

Sample DD-16 was collected from a hand-shovel pit excavated into a low-relief dune on the northeastern portion of the Denbigh Windblown Sands in northeastern McHenry County in the NW1/4 of Section 16, T. 159 N., R. 76 W. (Figure 19). This sample location is located approximately nine miles northeast of Bantry on North Dakota Trust Lands.

Sample DD-17

Sample DD-17 was collected from a hand-shovel pit from a dune exposure on a high-relief dune on the southern margin of a larger dune field five miles southwest of Denbigh in central McHenry County in the SW1/4 of Section 17, T. 155 N., R. 77 W. (Figure 20).

Figure 15. View to the northeast along high-relief dunes on North Dakota Trust Lands in southeastern McHenry County (T.155N., R.76W., Sec.36, NE1/4). Sample No. DD-12 was collected at this location.

Figure 16. View to the north of high-relief dunes in southeastern McHenry County approximately one mile north of Bald Butte (T.154N., R.75W., Sec.19, NE1/4.). Sample No. DD-13 was collected from dune deposits just west of this area.

Figure 17. View to the north of high-relief dunes in southeastern McHenry County (T.155N., R.76W., Sec.10, SW1/4) on the southern margin of the dune field approximately two miles north of Copperdahl Hill. Sample No. DD-14 was collected just south of this area. Image source: NAIP 2013 via Google Earth.

Figure 18. View to the northeast of high-relief dunes on the western margin of a large dune field in southeastern McHenry County (T.154N., R.76W., Sec.24, SE1/4). approximately 1.5 miles West of Bald Butte. Sample No. DD-15 was collected at this location.

Figure 19. View to the west of low-relief dunes in northern McHenry County (T.159N., R.76W., Sec.16, NW1/4). Sample No. DD-16 was collected at this location which is half-way between Upham and Willow City. Image source: NAIP 2013 via Google Earth.

Figure 20. View to the northwest of high-relief dunes at the southern edge of a dune field in central McHenry County 5.5 miles south of Denbigh (T.155N., R.77W., Sec.17, SW1/4). Sample No. DD-17 was collected at this location. Light scattered snow is present across the area in late October 2019.

Sample DD-18

Sample DD-18 was collected from a hand-shovel pit excavated into a low-relief dune on the southeastern most extent of the Denbigh Windblown Sands in southeastern McHenry County in the SE1/4 of Section 36, T. 153 N., R. 75 W. (Figure 21). This sample location is located approximately 10 miles north of Anamoose on North Dakota Trust Lands.

Sample DD-19

Sample DD-19 was collected from a hand-shovel pit from a dune exposure on an area of localized high-relief dunes on the northwestern portion of the Denbigh Windblown Sands in northwestern McHenry County in the NE1/4 of Section 33, T. 158 N., R. 78 W. (Figure 22). This sample location is located approximately six miles southwest of Bantry.

Sample DD-20

Sample DD-20 was collected from a hand-shovel pit excavated into a low-relief dune on the northwestern portion of the Denbigh Windblown Sands in northwestern McHenry County in the SW1/4 of Section 5, T. 157 N., R. 78 W. (Figure 23). This sample location is located approximately 8 miles southwest of Bantry.

Sample DD-21

Sample DD-21 was collected from a hand-shovel pit along the crest of a dune exposure on an area of localized high-relief dunes two miles south of Denbigh on the south-central portion of the Denbigh Windblown Sands in central McHenry County in the SW1/4 of Section 28, T. 156 N., R. 77 W. (Figure 24). This sample location is within U.S. Bureau of Land Management surface minerals land and is next to North Dakota's first active proppant sand production area.

Sample DD-22

Sample DD-22 was collected from a hand-shovel pit along the crest of a dune exposure on an area of localized high-relief dunes two miles south of Denbigh on the south-central portion of the Denbigh Windblown Sands in central McHenry County in the SW1/4 of Section 28, T. 156 N., R. 77 W. (Figure 25). This sample location is also within U.S. Bureau of Land Management surface minerals land, 542 yards (165 m) north of the DD-21 sample location.

Figure 21. Oblique view to the north of low-relief dunes on North Dakota Trust Lands in southeastern McHenry County (T.153N., R.75W., Sec.36, SE1/4). Sample No. DD-18 was collected at this location which is 5.5 miles southwest of Orrin and one mile east of Round Lake. Image source: NAIP 2013 via Google Earth.

Figure 22. View to the north of high-relief dunes in northwestern McHenry County (T.158N., R.78W., Sec.33, NE1/4). Sample No. DD-19 was collected near this location which is six miles southwest of Bantry. Additional high-relief dunes can be seen in the right background. Light late-October snow drapes the dune exposures.

Figure 23. View to the north of low-relief dunes in northwestern McHenry County (T.157N., R.78W., Sec.5, SW1/4) eight miles southwest of Bantry. Sample No. DD-20 was collected in this area. Image source: NAIP 2003 via Google Earth.

Figure 24. Dune face exposure on a high-relief dune located on a BLM Surface Mineral tract just south of Denbigh (T.156N., R.77W., Sec.28, SW1/4). Sample No. DD-21 was collected from the excavation in this photograph.

Figure 25. View to the east of high-relief dunes located on a BLM Surface Mineral tract just south of Denbigh (T.156N., R.77W., Sec.28, SW1/4). Sample No. DD-22 was collected from this location on the back side of this high-dune crest. The highest dunes in this area are well over 60 feet (18.3 m).

DESCRIPTON OF TESTING RESULTS

Samples of windblown sand were submitted for testing 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 (Table 2). 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 winter of 2019-2020.

Sample Preparation

All samples submitted for testing were prepared for analysis by washing on the #200 sieve, drying, and disassociation (Table 3). Gradational analysis was first performed on prepared samples to determine the dominant sand size fractions (Table 4). 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 5). Qualitative and quantitative XRD mineralogy was performed on prepared sand samples in order to provide a more accurate assessment of sand mineralogy.

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 5) or in graphical form on a grain-size distribution diagram (Figure 26).

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 26). 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 26) 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).

Table 2. Proppant Testing Analytical Summary of Eolian Sands in McHenry County

Sample No.	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						
DD-1	70/140	82.1	5K	5.8	0.6	0.8	0.165	0.152	42.4	0.35	84.3	1.52
DD-2	40/70	83.2	4K	5.9	0.6	0.8	0.306	0.256	15.0	0.41	87.6	1.60
DD-3a	40/70	81.4	4K	5.8	0.6	0.7	0.226	0.211	27.3	0.25	86.7	1.58
DD-3b	70/140	79.7	6K	6.0	0.5	0.8	0.226	0.211	44.2	0.28	85.6	1.53
DD-4a	40/70	79.2	5K	5.3	0.5	0.8	0.320	0.293	37.3	0.31	89.0	1.59
DD-4b	70/140	81.8	6K	7.7	0.5	0.8	0.320	0.293	67.2	0.41	86.7	1.53
DD-5	70/140	74.7	5K	6.3	0.6	0.8	0.261	0.216	66.9	0.40	84.4	1.50
DD-6	70/140	75.7	4K	6.2	0.6	0.8	0.178	0.153	37.2	0.34	82.9	1.44
DD-7	70/140	74.0	5K	6.7	0.6	0.8	0.226	0.205	37.2	0.35	84.5	1.49
DD-8	40/70	71.9	6K	6.8	0.7	0.6	0.307	0.280	9.5	0.32	88.7	1.59
DD-9	70/140	68.4	6K	6.5	0.7	0.6	0.183	0.164	13.4	0.32	85.6	1.50
DD-10a	40/70	79.0	4K	5.4	0.6	0.8	0.221	0.212	17.2	0.24	87.5	1.52
DD-10b	70/140	75.5	6K	7.1	0.6	0.8	0.221	0.212	31.2	0.29	85.4	1.57
DD-11a	40/70	82.0	5K	5.0	0.6	0.8	0.233	0.212	21.2	0.20	89.1	1.63
DD-11b	70/140	76.7	5K	6.9	0.6	0.8	0.233	0.212	39.5	0.28	85.6	1.57
DD-12a	40/70	81.9	4K	6.4	0.6	0.8	0.245	0.228	38.9	0.18	87.7	1.62
DD-12b	70/140	72.2	6K	6.8	0.6	0.8	0.245	0.228	48.4	0.23	86.0	1.57
DD-13a	40/70	81.1	5K	5.8	0.6	0.8	0.250	0.234	14.0	0.22	88.4	1.65
DD-13b	70/140	75.0	6K	7.4	0.6	0.8	0.250	0.234	21.6	0.31	86.2	1.59
DD-14	40/70	78.2	5K	6.2	0.6	0.8	0.458	0.408	18.7	0.26	90.3	1.66
DD-15	40/70	81.9	5K	5.9	0.7	0.8	0.307	0.281	20.0	0.27	88.5	1.61
DD-16	70/140	73.3	4K	6.7	0.5	0.8	0.153	0.138	15.0	0.36	87.7	1.54
DD-17	40/70	72.8	5K	6.4	0.6	0.8	0.311	0.294	13.3	0.25	83.5	1.62
DD-18	40/70	74.0	6K	5.0	0.6	0.8	0.322	0.274	15.1	0.30	88.9	1.61
DD-19	70/140	69.7	5K	5.7	0.5	0.8	0.155	0.146	14.9	0.30	83.8	1.55
DD-20	70/140	72.3	5K	7.6	0.5	0.8	0.174	0.162	15.0	0.61	87.7	1.54
DD-21	50/140	71.4	7K	6.6	0.5	0.8	0.252	0.223	20.5	0.31	87.3	1.59
DD-22	70/140	71.1	6K	6.1	0.5	0.8	0.216	0.197	25.2	0.26	85.5	1.58

[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 3. Wash Loss on Bulk Sample

Sample No.	Wash Loss (%)	Over-Size Waste (%)	Fines Waste (%)	Sample Total	
				Waste	Product[1]
DD-1	17.34	0.3	11.7	29.4	70.6
DD-2	14.43	13.2	3.2	30.8	69.2
DD-3	11.81	1.9	1.5	15.2	84.8
DD-4	2.06	16.9	0.9	19.9	80.1
DD-5	13.39	9.6	5.1	28.1	71.9
DD-6	16.79	1.7	16.2	34.7	65.3
DD-7	16.72	3.8	5.1	25.6	74.4
DD-8	9.20	13.1	1.6	24.0	76.0
DD-9	21.45	1.1	9.1	31.7	68.3
DD-10	4.80	1.6	2.1	8.5	91.5
DD-11	4.50	4.6	6.4	15.6	84.4
DD-12	3.20	4.1	1.9	9.1	90.9
DD-13	3.55	4.8	3.1	11.4	88.6
DD-14	2.46	45.4	0.9	48.7	51.3
DD-15	2.13	11.7	0.4	14.2	85.8
DD-16	11.07	0.1	19.5	30.6	69.4
DD-17	3.46	13.7	0.3	17.5	82.5
DD-18	7.83	18	5.5	31.3	68.7
DD-19	5.60	0.1	14.6	20.3	79.7
DD-20	10.53	0.5	12.2	23.2	76.8
DD-21	3.64	7.5	3.7	14.9	85.1
DD-22	3.40	2.4	2.7	8.5	91.5

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

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

	Sample No.	DD-1	DD-2	DD-3	DD-4	DD-5	DD-6	DD-7	DD-8	DD-9	DD-10	DD-11	DD-12	DD-13	DD-14	DD-15	DD-16	DD-17	DD-18	DD-19	DD-20	DD-21	DD-22
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	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	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	0.5	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0
	30	0.1	4.8	0.2	2.4	3.3	0.3	0.7	2.4	0.1	0.1	0.7	0.6	0.5	16.7	2.3	0.0	0.2	6.0	0.0	0.0	1.3	0.2
	40	0.3	10.1	1.9	14.9	7.7	1.8	3.8	12.0	1.2	1.7	4.2	3.6	4.5	29.7	9.7	0.1	14.0	13.1	0.1	0.5	6.5	2.3
	45	0.5	9.2	3.7	13.8	6.7	2.3	4.4	12.7	1.9	3.8	6.3	5.9	6.9	15.1	12.4	0.4	14.6	11.1	0.2	1.2	7.0	3.6
	50	2.1	11.7	7.8	16.5	8.9	4.6	8.0	15.8	3.9	8.1	10.5	10.7	11.8	11.5	17.7	2.2	18.7	12.4	0.9	3.8	9.9	6.8
	60	5.6	15.6	16.4	18.5	12.7	7.9	14.4	18.3	8.5	16.3	15.8	19.1	19.9	9.5	22.1	5.8	21.2	14.2	3.6	8.0	15.5	13.1
	70	9.2	12.8	19.2	11.7	11.9	9.5	15.2	12.8	10.2	19.7	12.5	17.7	16.6	5.8	14.4	7.3	13.3	10.5	7.1	11.4	13.8	15.6
	80	14.0	11.1	19.4	8.9	12.2	11.3	15.4	9.8	14.6	15.5	11.6	15.7	13.9	4.0	10.1	9.8	8.4	8.2	12.7	14.3	14.2	18.8
	100	19.5	9.5	16.0	6.3	12.4	13.4	14.2	7.6	19.0	15.8	12.1	12.7	11.1	3.2	6.5	14.3	5.6	7.6	21.4	18.0	13.1	18.5
	120	21.7	7.1	10.0	4.2	11.4	16.2	11.4	4.5	17.2	11.6	12.1	8.4	7.8	2.4	3.4	22.5	2.8	6.5	25.1	18.6	10.0	13.2
	140	12.7	3.7	3.7	1.9	6.7	13.2	6.3	2.3	11.7	5.2	7.5	3.6	4.0	1.1	1.1	15.8	0.8	4.0	13.4	10.4	4.9	5.1
	170	7.7	2.0	1.2	0.6	3.6	9.5	3.4	1.1	6.5	1.6	4.0	1.4	2.0	0.6	0.3	11.4	0.3	2.9	9.7	7.9	2.6	2.2
	200	5.2	1.3	0.4	0.3	2.1	7.5	2.3	0.7	4.9	0.6	2.4	0.5	1.1	0.3	0.1	8.5	0.1	2.4	4.8	0.6	1.2	0.6
	Pan	1.2	0.4	0.0	0.0	0.2	2.5	0.4	0.0	0.3	0.0	0.3	0.0	0.1	0.0	0.0	2.0	0.0	0.7	0.9	5.2	0.1	0.0
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	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
DD-1	2.9	17.5	68.0	82.9
DD-2	31.1	49.4	31.5	59.9
DD-3	13.4	47.1	49.1	84.7
DD-4	45.2	60.5	21.3	51.5
DD-5	23.3	40.3	42.7	67.4
DD-6	8.7	24.3	54.1	71.6
DD-7	16.2	42.0	47.4	77.0
DD-8	40.5	59.5	24.2	55.3
DD-9	7.0	24.5	62.5	81.2
DD-10	13.6	48.0	48.1	84.2
DD-11	21.0	45.2	43.2	71.6
DD-12	20.2	53.4	40.4	77.3
DD-13	23.1	55.1	36.7	73.2
DD-14	56.3	41.9	10.7	26.0
DD-15	39.8	66.6	21.0	57.5
DD-16	2.6	13.9	55.5	75.5
DD-17	47.3	65.5	17.1	52.2
DD-18	36.5	44.4	24.3	51.1
DD-19	1.2	11.2	68.5	83.3
DD-20	5.6	21.9	54.9	80.8
DD-21	23.4	44.5	40.6	71.5
DD-22	12.7	37.8	53.7	84.3

Size Range	0 - 25	25 - 50	50 - 75	>75
Average	22.3	41.6	41.6	69.1

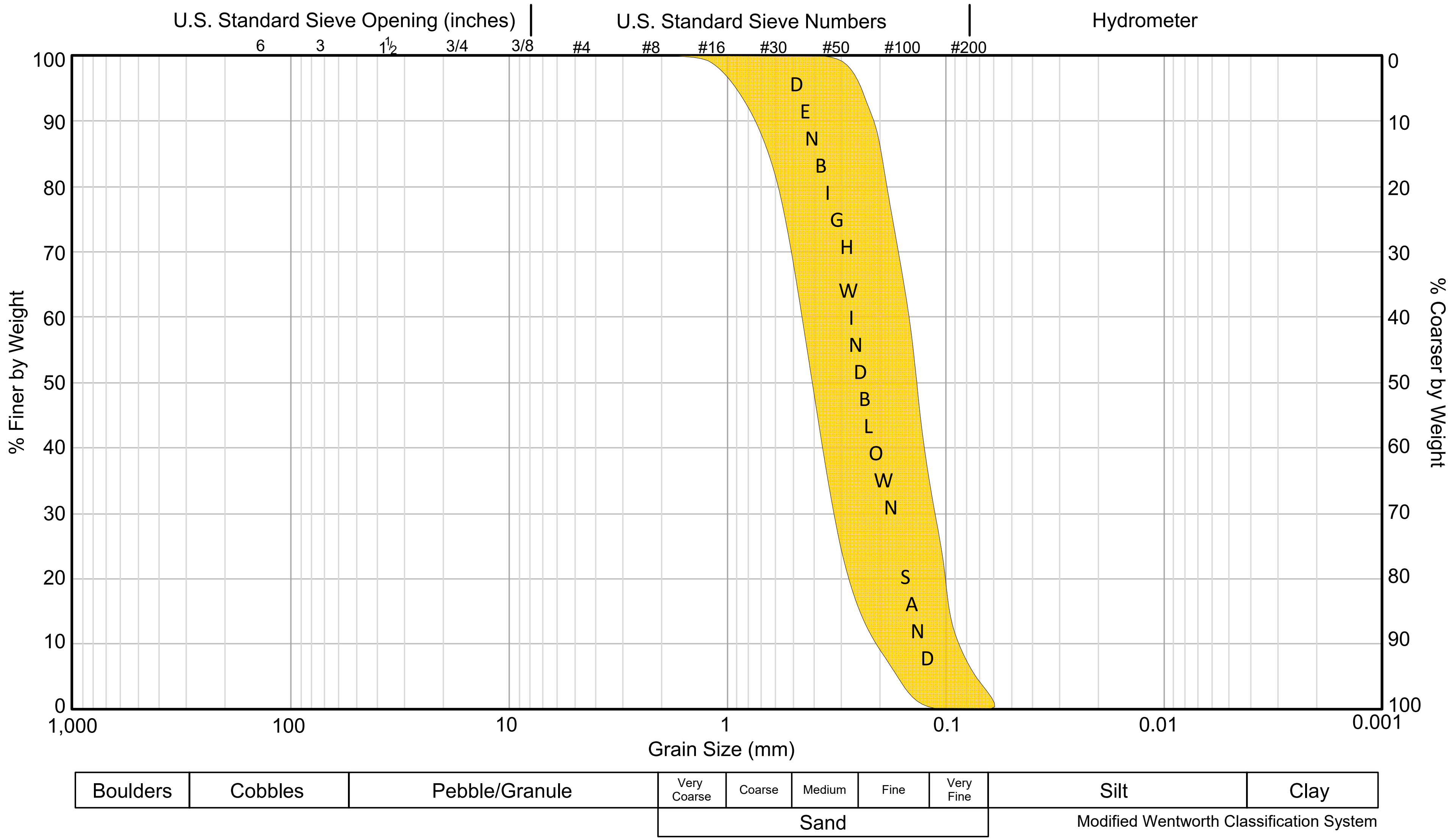

Figure 26. Range of 22 grain-size distribution curves (shaded-yellow) from windblown deposits in the Denbigh Dunes area, McHenry County, North Dakota. These sands are well sorted and medium to very-fine grained according to the Modified Wentworth Classification System.

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 2).

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 I - 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). All samples tested had sphericity values generally ≥ 0.8 with roundness values commonly ≥ 0.6 (Figure 27). These values are within desired specifications, particularly for sphericity factors.

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 28) but are considerably lower than other sand sources tested in North Dakota (Anderson and others, 2019). Acid solubility on these eolian sands ranged from 5.0 to 7.6% (Table 2).

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 22 samples were below the recommended limit of 250 FTU (Figure 29). The samples ranged from 9.5 to 67.2 FTU (Table 2).

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 28 sand samples from 22 locations. When the largest size fractions (40/70 & 70/140) were similar in weight percent, both size classes were tested.

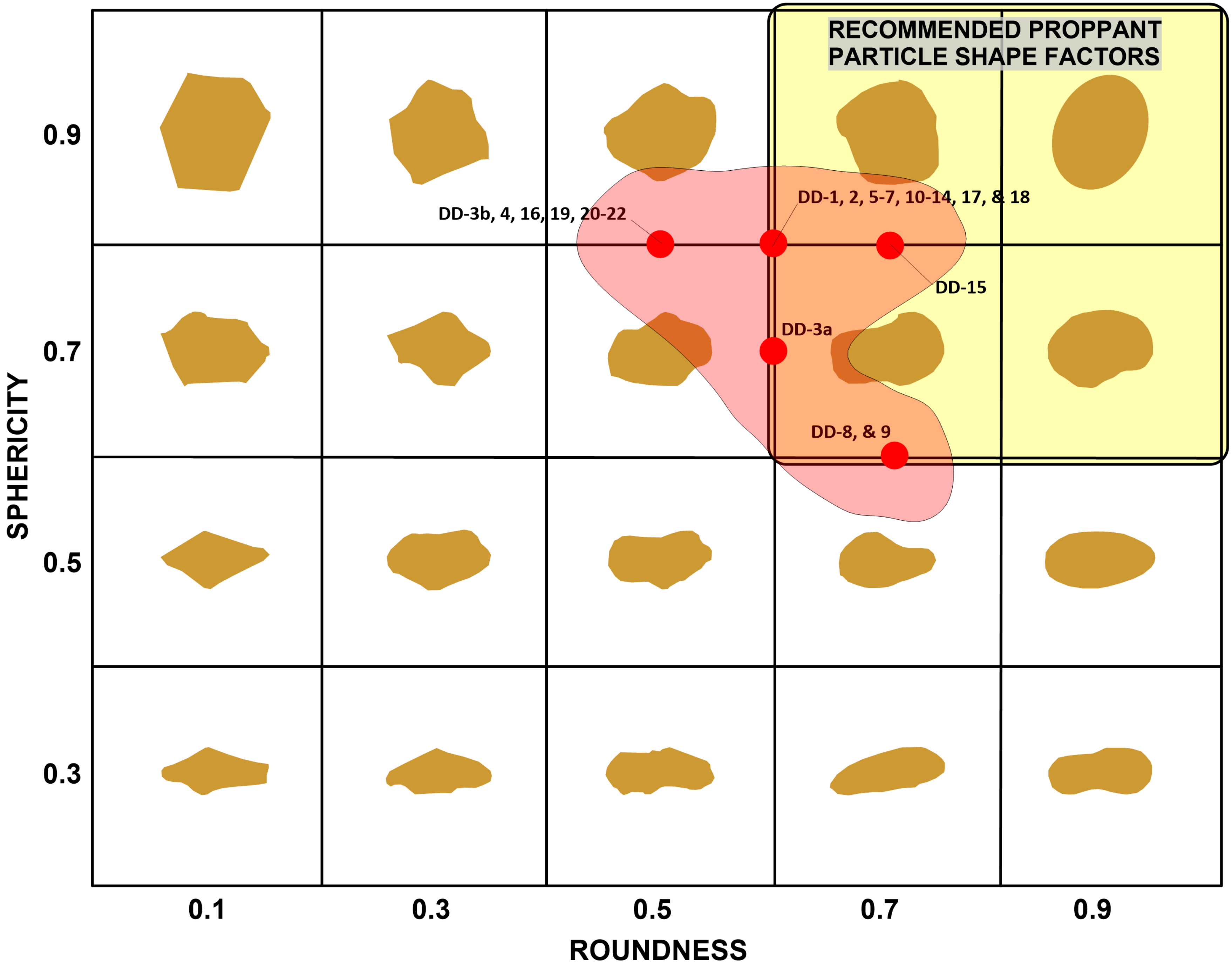

Figure 27. Comparison of sphericity and roundness values for eolian sand samples from the Denbigh Dunes north-central North Dakota. Samples from these deposits have particle shape factor values (shaded red) that are within the range of desired specifications (shaded yellow) for frac sand as compared to Ottawa White silica sands.

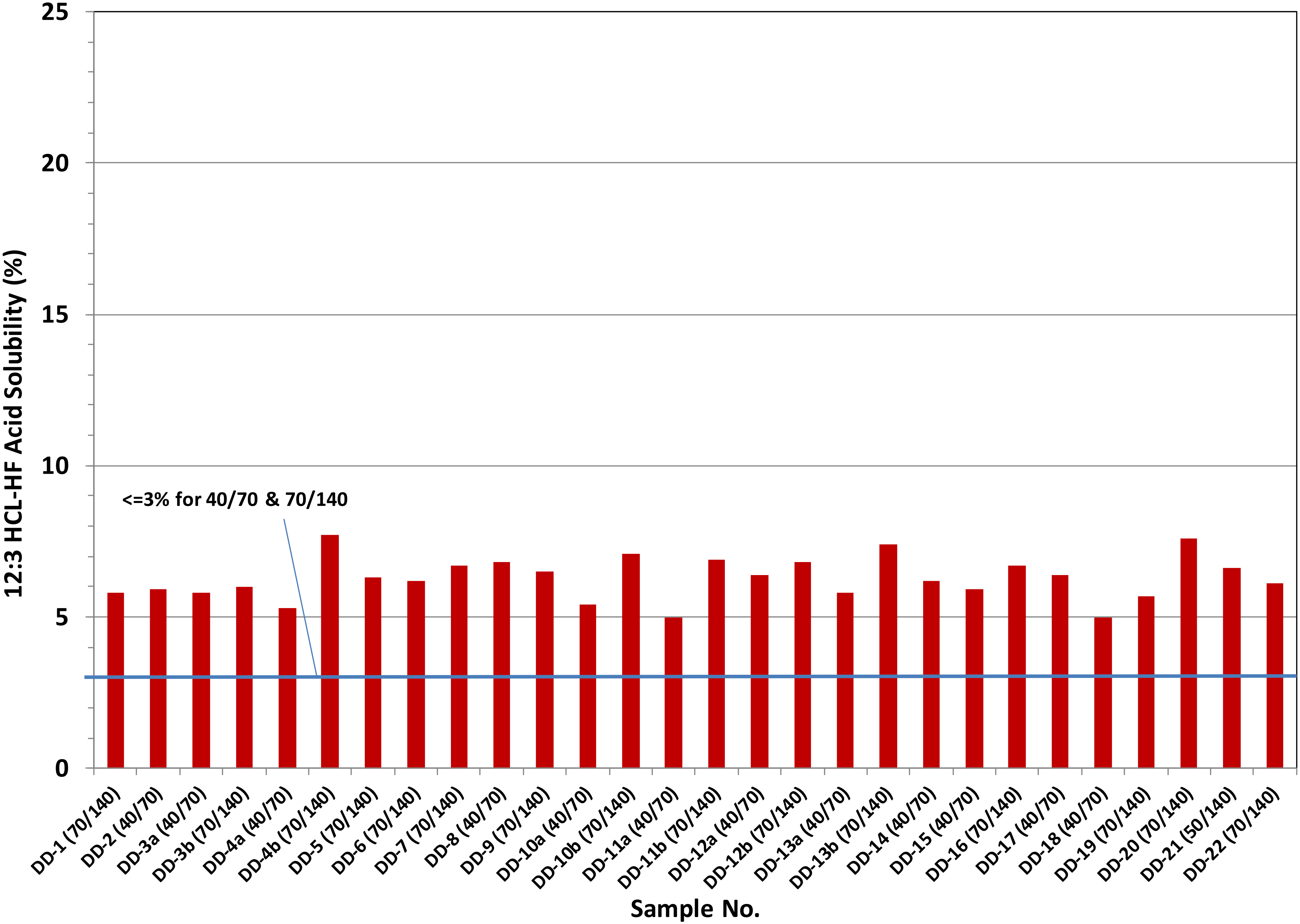

Figure 28. Comparison of hydrochloric:hydrofluoric acid solubility results for windblown sand samples from the Denbigh Dunes. Recommended specifications for acid solubility on 40/70 & 70/140 sands are less than or equal to 3%.

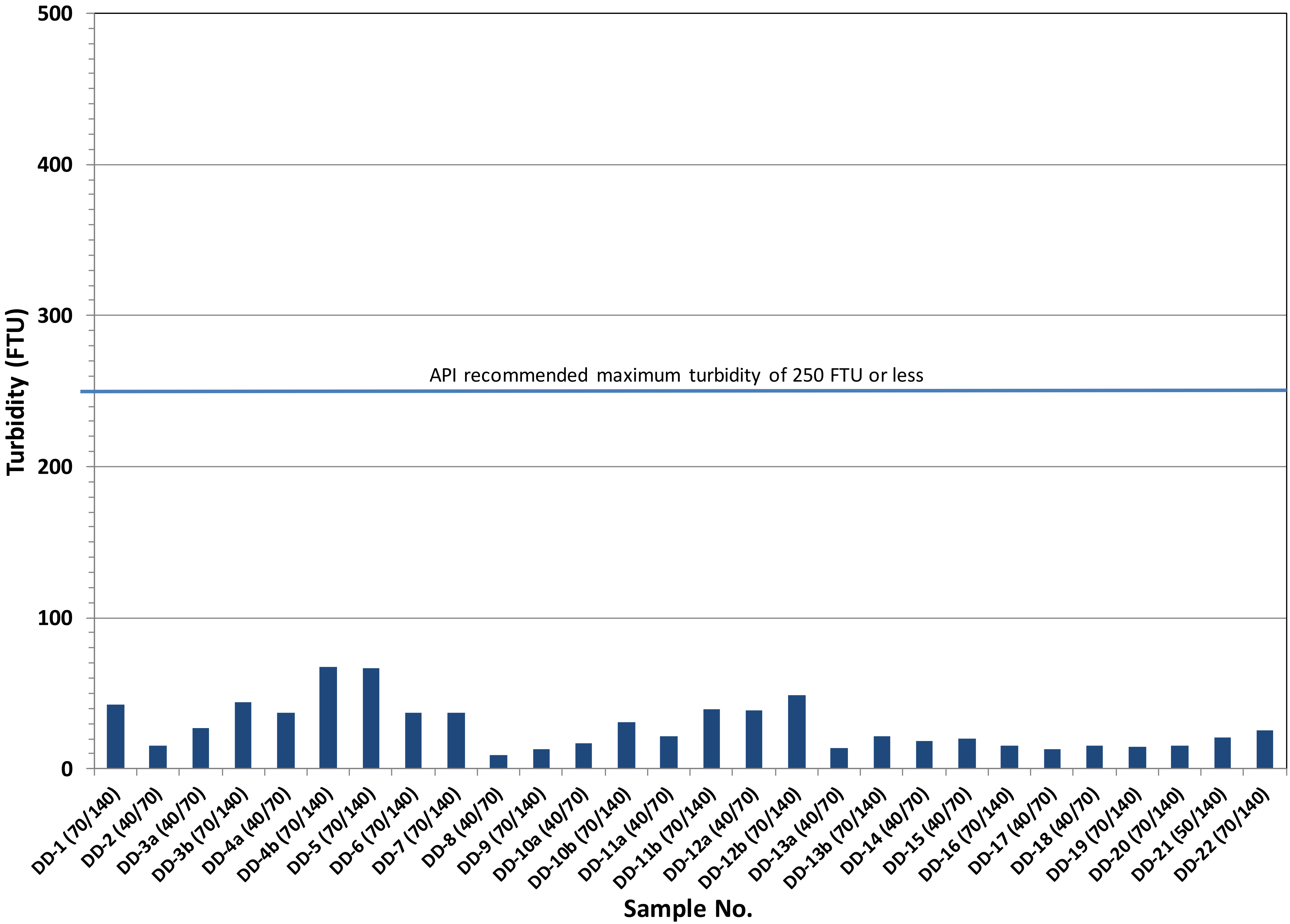

Figure 29. Comparison of turbidity results for washed windblown sand samples from the Denbigh Dunes. Recommended API specifications for turbidity are 250 FTU or less. All samples tested are well below this criteria.

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 6,000 psi (4K to 6K) within the 40/70 and 70/140 size classes. A 7,000 psi (7K) crush resistance was returned on a 50/140 sand (Sample No. DD-21) from the Denbigh Dunes (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 0.18 to 0.61%, which is probably to be expected from a washed, sized sample cut (Table 2, Figure 30). LOI quantifies the amount of undesireable organic material in a sample.

Mineralogy (X-Ray Diffraction)

Sample geochemistry was determined using qualitative and quantitative X-ray diffraction (XRD) on all washed and sized sand samples (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 68 to 83%, feldspar ranged from 16 to 32%, and clay contents ranged from 0 to 3% (Figures 31 & 32). In comparison, Ottawa White silica sands are commonly 99% quartz. XRD phase diagrams for all samples tested are included in Appendix II.

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 (Table 2) ranged from 83 to 90 pounds per cubic foot (pcf) with an average of 87 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 eolian sands, ranged from 1.4 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 III.

Table 6. Crush Resistance Testing Data Summary

Sample No.	Size Class	K-Value	Test Stress (psi)					
			3000	4000	5000	6000	7000	8000
			Fines Generated (%)					
DD-1	70/140	5K	--	--	8.93	11.55	--	--
DD-2	40/70	4K	--	5.97	10.58	--	--	--
DD-3a	40/70	4K	--	7.82	11.87	--	--	--
DD-3b	70/140	6K	--	--	--	9.09	10.60	--
DD-4a	40/70	5K	--	--	7.10	10.94	--	--
DD-4b	70/140	6K	--	--	--	6.98	10.70	--
DD-5	70/140	5K	--	--	8.13	11.92	--	--
DD-6	70/140	4K	--	8.13	11.87	--	--	--
DD-7	70/140	5K	--	--	7.38	10.08	--	--
DD-8	40/70	6K	--	--	--	8.48	12.89	--
DD-9	70/140	6K	--	--	--	8.73	12.54	--
DD-10a	40/70	4K	--	7.88	10.68	--	--	--
DD-10b	70/140	6K	--	--	--	8.99	12.18	--
DD-11a	40/70	5K	--	--	9.49	11.98	--	--
DD-11b	70/140	5K	--	--	8.97	10.87	--	--
DD-12a	40/70	4K	--	8.58	11.15	--	--	--
DD-12b	70/140	6K	--	--	--	7.66	10.64	--
DD-13a	40/70	5K	--	--	9.73	13.45	--	--
DD-13b	70/140	6K	--	--		8.44	11.56	--
DD-14	40/70	5K	--	--	7.25	10.90	--	--
DD-15	40/70	5K	--	--	7.62	11.27	--	--
DD-16	70/140	4K	--	9.62	11.59	--	--	--
DD-17	40/70	5K	--	--	7.33	11.11		--
DD-18	40/70	6K	--	--	--	9.66	13.92	--
DD-19	70/140	5K	--	--	8.98	13.24		--
DD-20	70/140	5K	--	--	9.31	12.46		--
DD-21	50/140	7K	--	--	--	--	9.00	11.16
DD-22	70/140	6K	--	--	--	9.49	12.81	--

-- Stress point not tested.

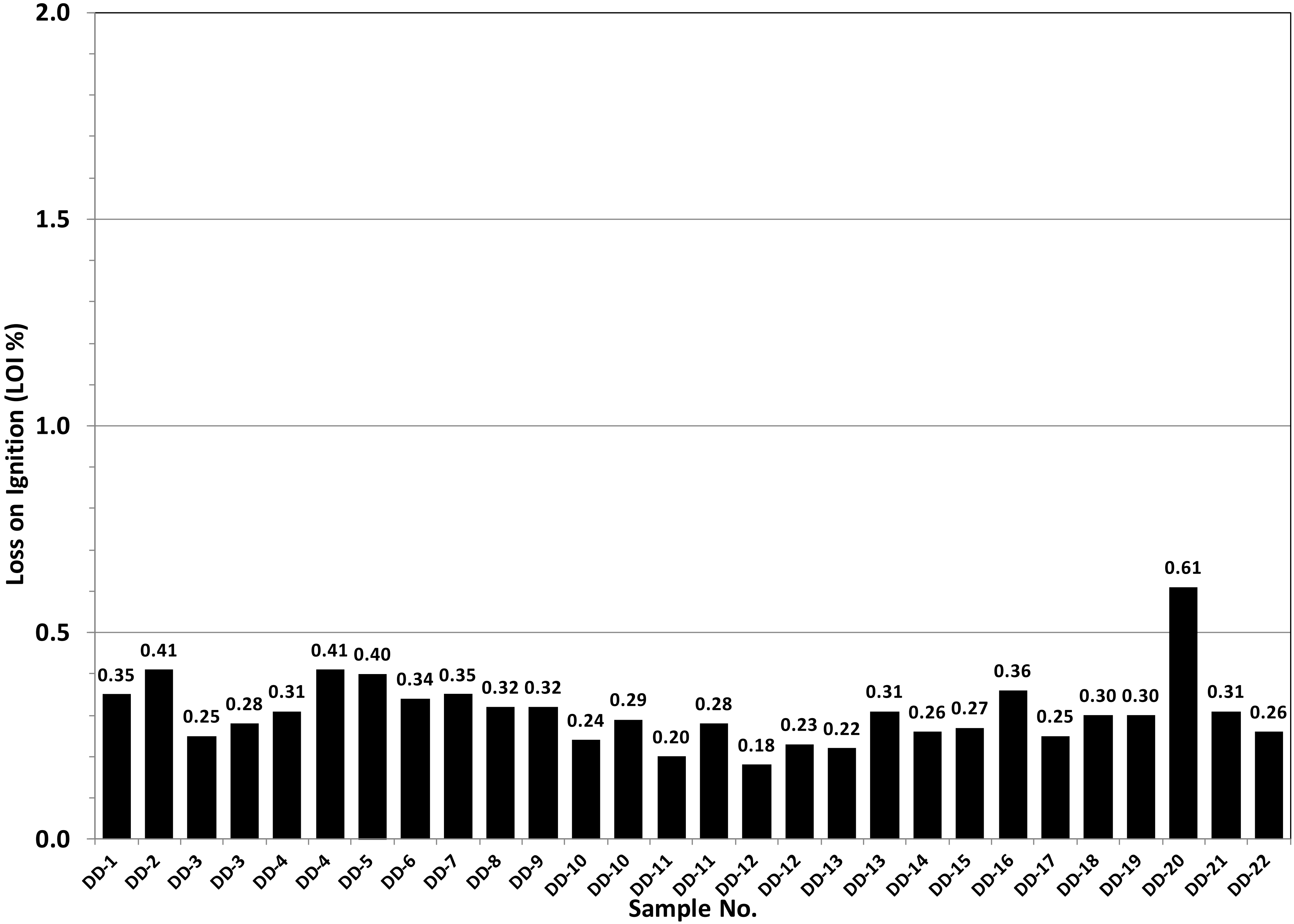

Figure 30. Graph of loss on ignition (LOI) of windblown sand from dune deposits in northern McHenry County, North Dakota. These sands are from the 40/70 and 70/140 size classes which are washed samples. The majority of samples are all less than 0.5 % LOI which suggests a low overall organic content of material such as detrital lignite.

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

Sample ID	Quartz	Feldspars			Clays		Carbonates			Other Minerals		
		Albite	Microcline	Feldspars*	Illite	Clays*	Calcite	Dolomite	Carbonates*	Clinochlore	Indialite	Magnetite
DD-1 (70/140)	82.1	--	--	17.9	--	0.0	--	--	--	--	--	--
DD-2 (40/70)	83.2	--	--	16.9	--	0.0	--	--	--	--	--	--
DD-3 (40/70)	81.4	--	--	18.6	--	0.0	--	--	--	--	--	--
DD-3 (70/140)	79.7	--	--	20.3	--	0.0	--	--	--	--	--	--
DD-4 (40/70)	81.8	--	--	17.4	--	1.9	--	--	--	--	--	--
DD-4 (70/140)	79.2	--	--	17.4	--	3.4	--	--	--	--	--	--
DD-5 (70/140)	74.7	--	--	25.3	--	0.0	--	--	--	--	--	--
DD-6 (70/140)	75.7	--	--	24.3	--	0.0	--	--	--	--	--	--
DD-7 (70/140)	74.0	--	--	24.6	1.4	1.4	--	--	--	--	--	--
DD-8 (40/70)	71.9	11.2	16.9	28.1	--	0.0	--	--	--	--	--	--
DD-9 (70/140)	68.4	13.2	18.4	31.6	--	0.0	--	--	--	--	--	--
DD-10 (40/70)	79.0	--	--	18.3	--	1.5	--	--	--	1.5	1.2	
DD-10 (70/140)	75.5	--	--	20.2	--	1.0	--	--	--	1.0	2.0	1.3
DD-11 (40/70)	82.0	--	--	17.1	--	0.9	--	--	--	0.9	--	
DD-11 (70/140)	76.7	--	--	20.9	--	1.0	--	--	--	1.0	--	1.5
DD-12 (40/70)	81.9	--	--	16.1	--	2.0	--	--	--	2.0	--	
DD-12 (70/140)	72.2	--	--	23.6	--	1.5	--	--	--	1.5	--	2.7
DD-13 (40/70)	81.1	--	--	17.5	--	1.4	--	--	--	1.4	--	
DD-13 (70/140)	75.0	--	--	20.4	--	2.8	--	--	--	2.8	--	1.8
DD-14 (40/70)	78.2	--	--	19.9	--	1.1	--	--	--	1.1	--	0.8
DD-15 (40/70)	81.9	--	--	16.9	--	1.2	--	--	--	1.2	--	--
DD-16 (70/140)	73.3	--	--	24.6	0.7	0.7	--	--	--	--	1.4	--
DD-17 (40/70)	72.8	--	--	24.8	1.3	1.3	--	--	--	--	1.2	--
DD-18 (40/70)	74.0	--	--	24.9	1.2	1.2	--	--	--	--		--
DD-19 (70/140)	69.7	--	--	27.9	1.8	1.8	--	--	--	--	0.6	--
DD-20 (70/140)	72.3	--	--	25.0	1.5	1.5	--	--	--	--	1.2	--
DD-21 (50/140)	71.4	--	--	26.5	1.4	1.4	--	--	--	--	0.7	--
DD-22 (70/140)	71.1	--	--	26.5	1.3	1.3	--	--	--	--	1.1	--

**Undifferentiated*

-- Mineral not detected

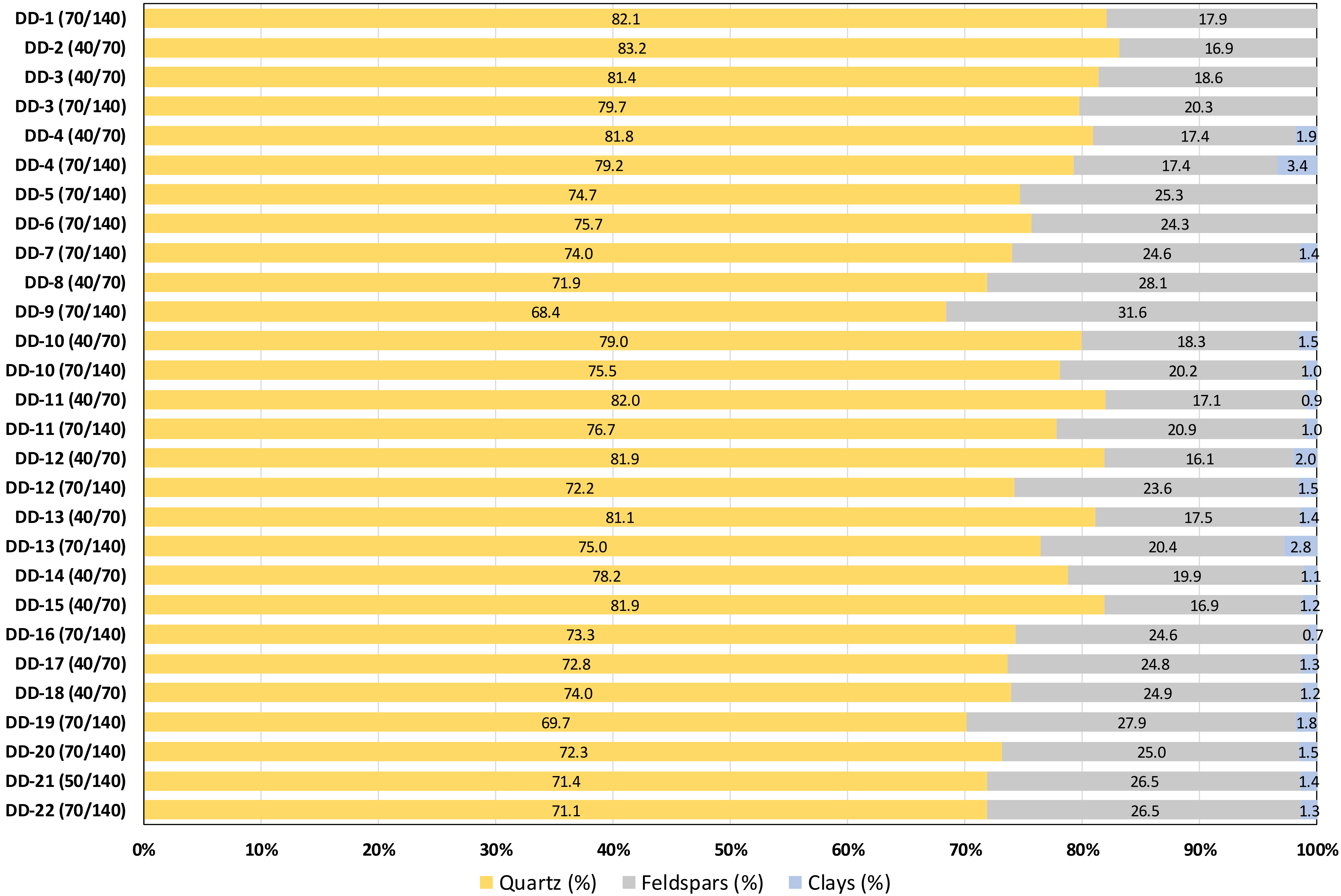

Figure 31. Summary mineralogy from X-ray diffraction (XRD) analysis of windblown sand found in dune deposits in northern McHenry County, North Dakota. Selected sand size classes, primarily in the 40/70 and 70/140 range, were analyzed. No carbonates were detected.

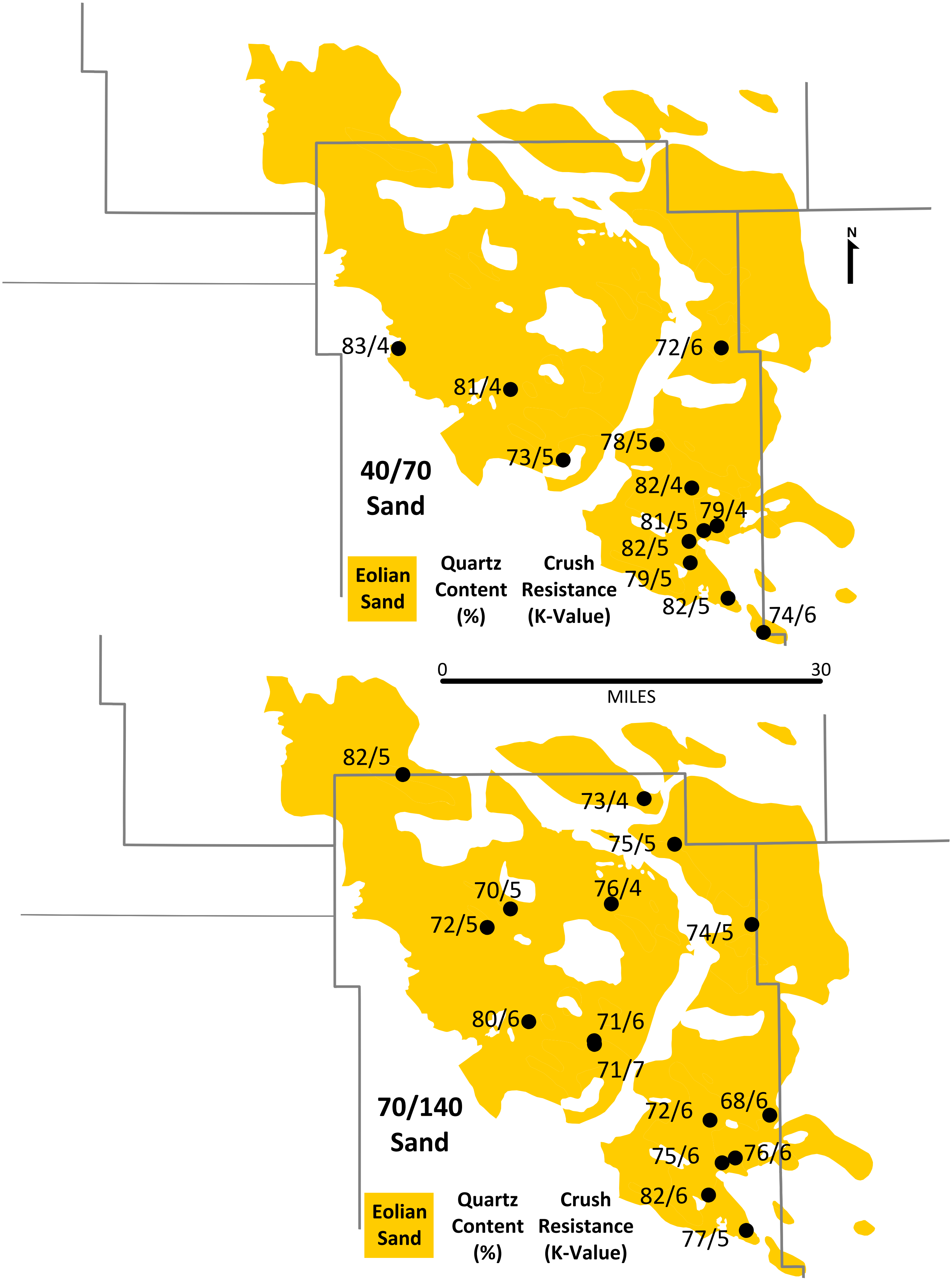

Figure 32. Quartz content and crush resistance values for 40/70 and 70/140 sand size classes of windblown sand in north-central North Dakota.

CONCLUSIONS

Eolian sand deposits in north-central North Dakota have favorable geologic characteristics for use as proppant based on current industry requirements. These deposits are found as low and high-relief sand dunes occurring in localized coalesced dune fields in as many as 81 separate areas. The sand is well sorted with sand grain size ranges dominantly in the finer size classes (40/70 & 70/140) and contain quartz contents that generally exceed 76% in washed materials. Crush-resistance testing typically ranges from 4,000 to 6,000 psi (4K to 6K) in the 40/70 and 70/140 sand sizes. A 7,000 psi (7K) value was returned on tested sand in the 50/140 size class. Particle shape factors for these sand grains fall within desired industry specifications for sphericity and roundness. Sand quality appears to increase to the southeast across McHenry County in areas with the greatest amount of downwind transport. Additional material processing may still 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.

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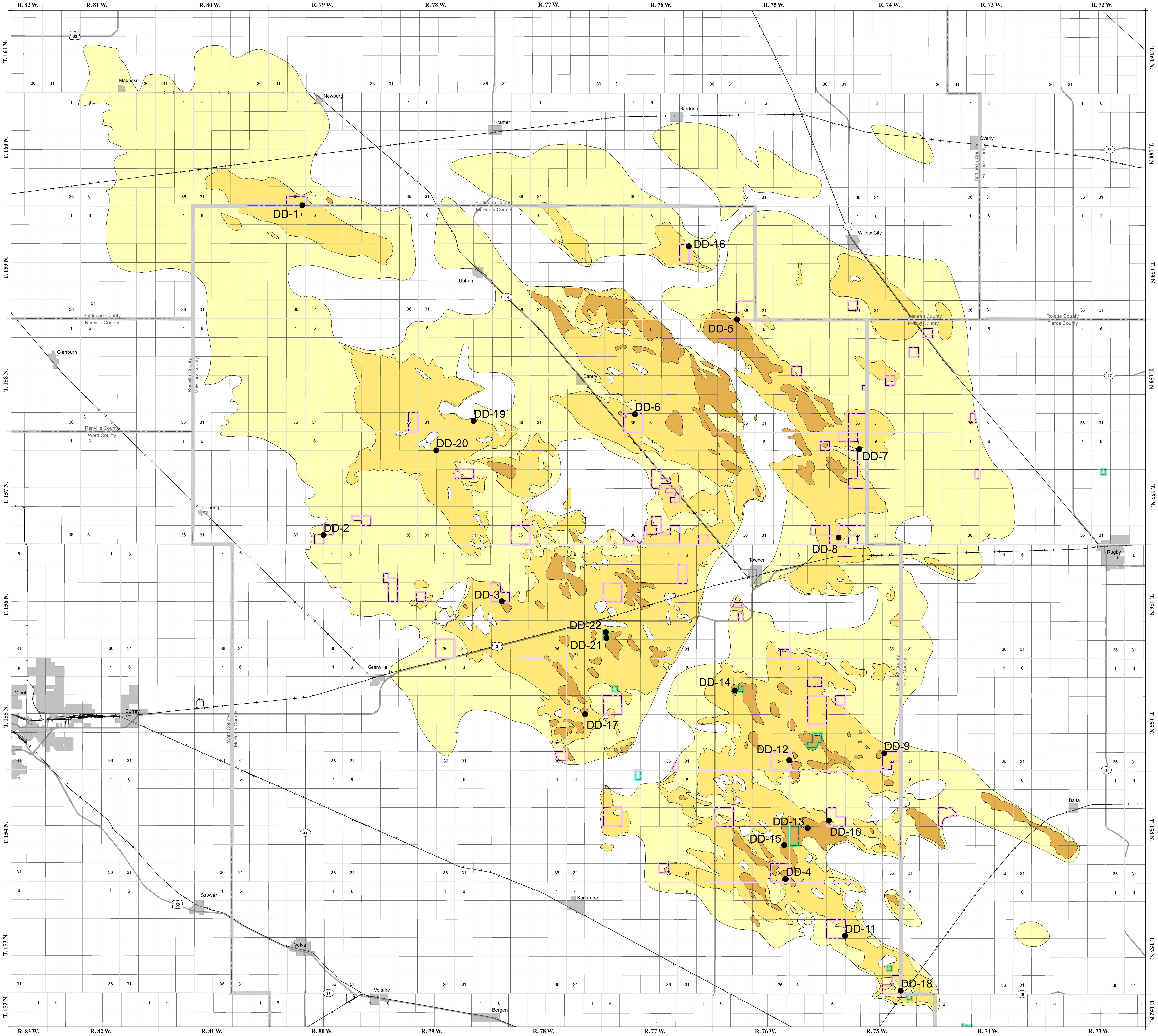
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Reources

Windblown Sand Deposits in North-Central North Dakota



DISCUSSION

Windblown sand in north-central North Dakota was evaluated in 2019 in support of the exploration for potential sources of in -basin proppant sand. A total of 22 samples were collected from locations across central and northern McHenry County and evaluated for proppant use. Samples were collected from high-relief dune fields and areas of gently undulating sheet sands with occasional low-relief dunes. Windblown sand from this area has been found 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).

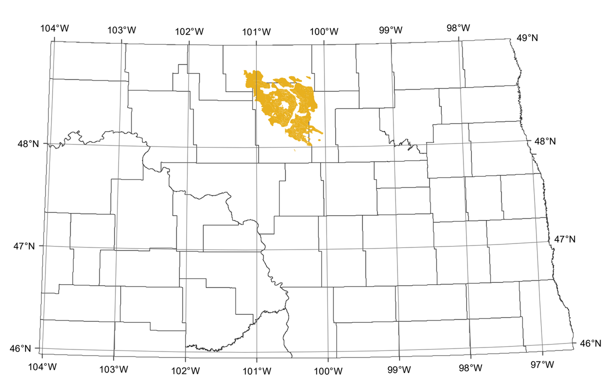
Qodl — Windblown sand in low-relief dunes with relief typically less than 10 feet (3 m).

Qoct — Windblown sand as thin undulating tabular sheet sands with scattered low-relief dunes mantling glaciolacustrine sands.

● Samples collected and tested for proppant use.

Other Features

Highways
County Boundaries
River
Railroad
State Trust Land
BLM Surface and Mineral Lands



Denbigh Dunes, North Dakota

N
W E
S

Scale 1:150,000

0 3 6

Miles

Mercator Projection
North American 1983 Datum
Central Meridian 100°37'30"W
Standard Parallel 1: 48°0'0"N

MAP COMPILATION REFERENCES

Bluemle, J.P., 1982, Geology of McHenry County, North Dakota, North Dakota Geological Survey, Bulletin 74, Part 1, Plate I.

Clayton, L., Moran, S.R., Bluemle, J.P., and Carlson, C.G., 1980, Geologic Map of North Dakota, U.S. Geological Survey-N.D. Geological Survey, 1:500,000 scale map.

Lord, M.L., 1988, Surface Geology of the Souris River Map Area, North Dakota Geological Survey, Atlas Series Map AS-4-A1, 1:250,000 scale map.

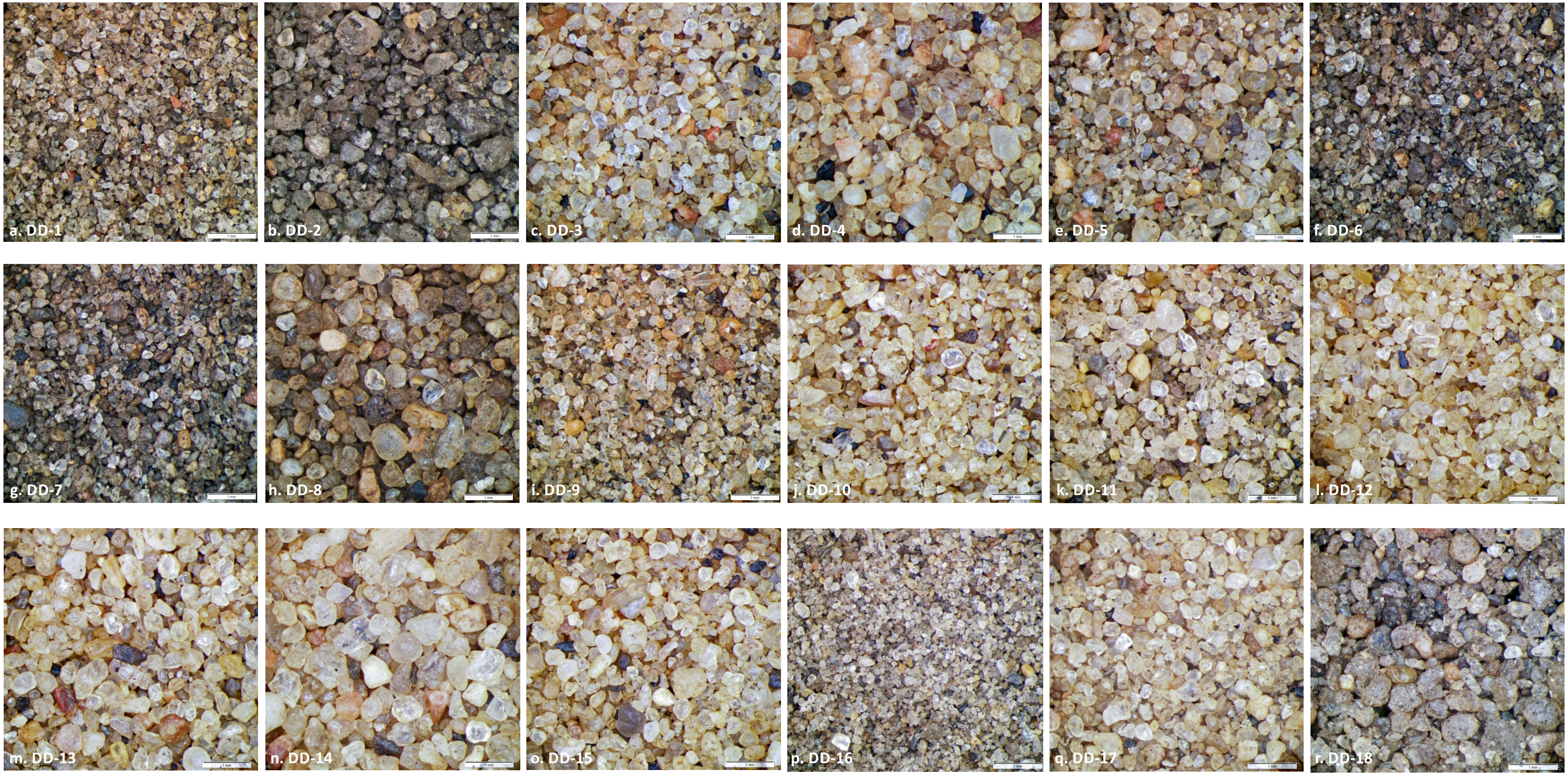
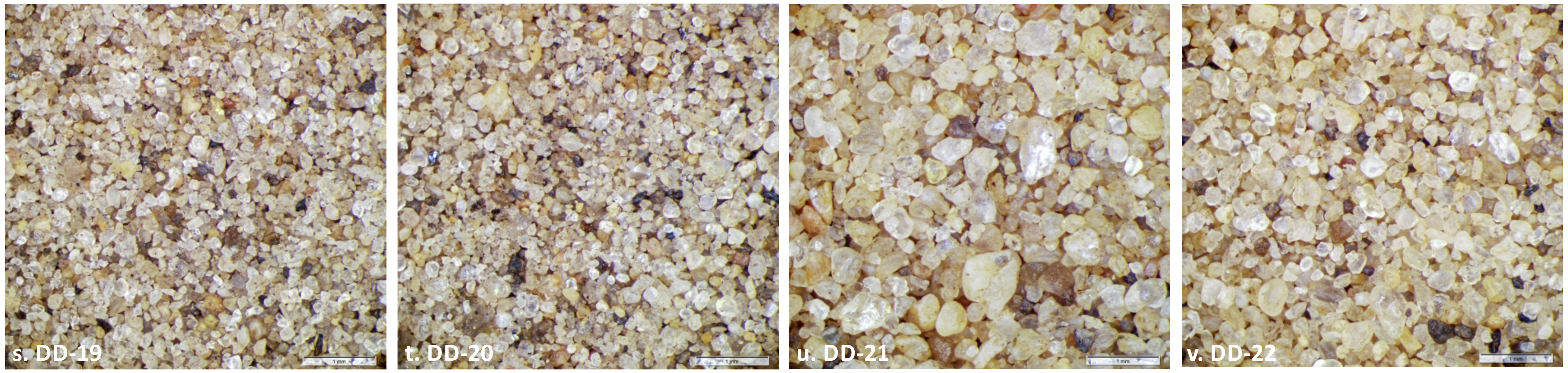
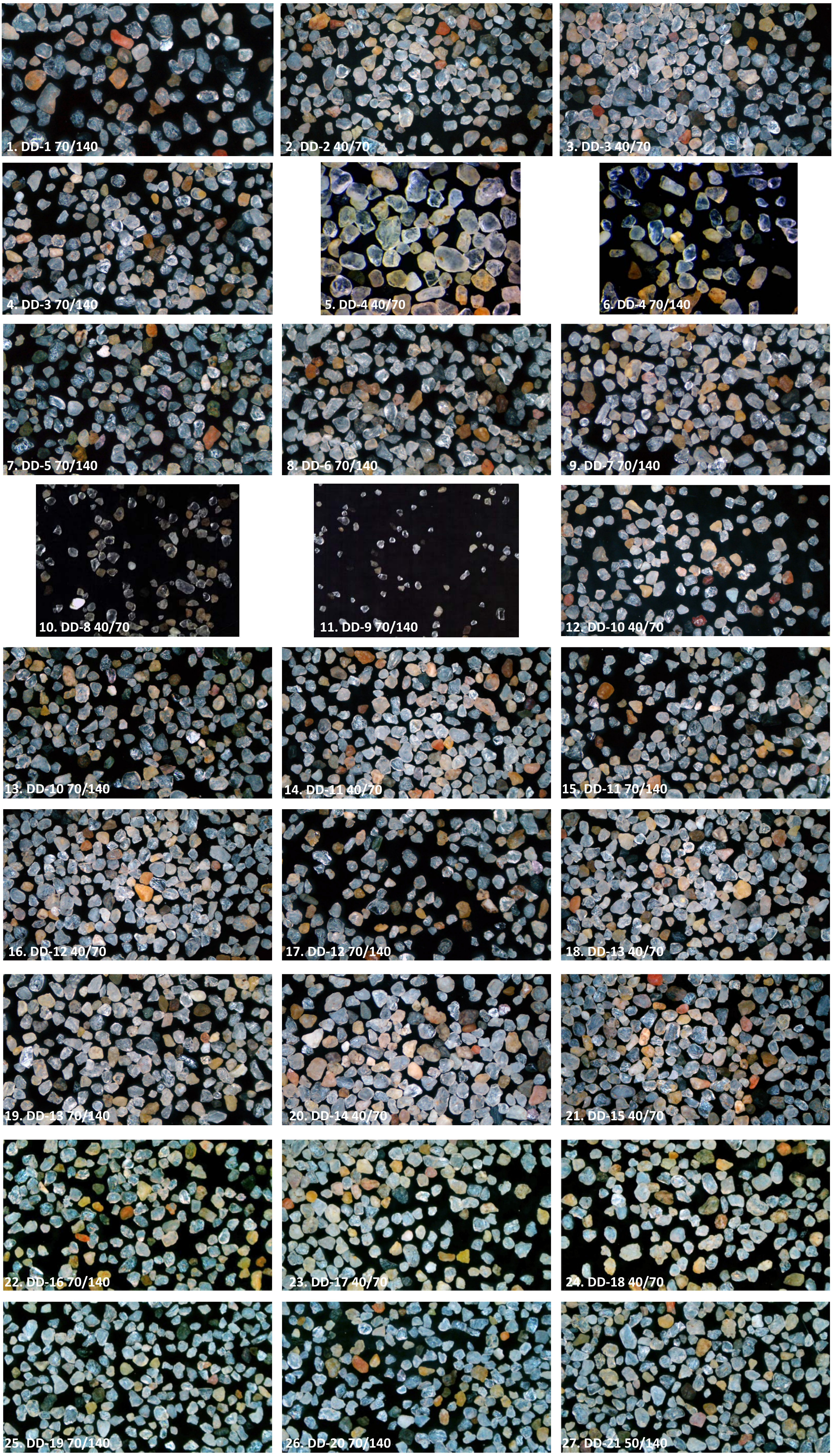


Plate II. Bulk sand (25x) photomicrographs of samples from the Denbigh Dunes in McHenry County, North Dakota. Photomicrographs a-c, e-h, k, p, r, and t are from dunes of low relief. Photomicrographs d, i, j, l-o, q, s, u, and v are from high-relief (>10 ft) dunes. Quartz grains tend to be clear to opaque. Dark-colored grains can be feldspars, detrital lignite, or sand grains from the weathering of igneous and metamorphic rocks.





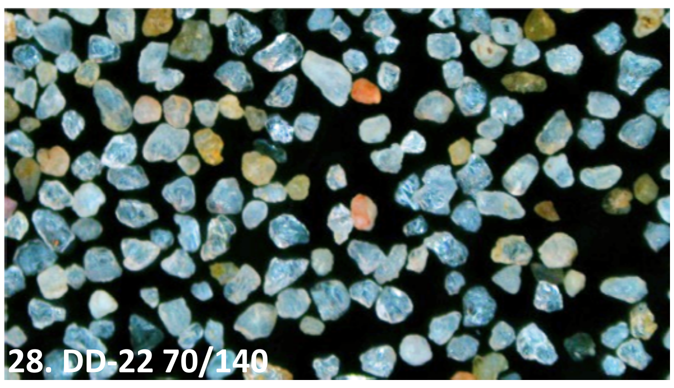
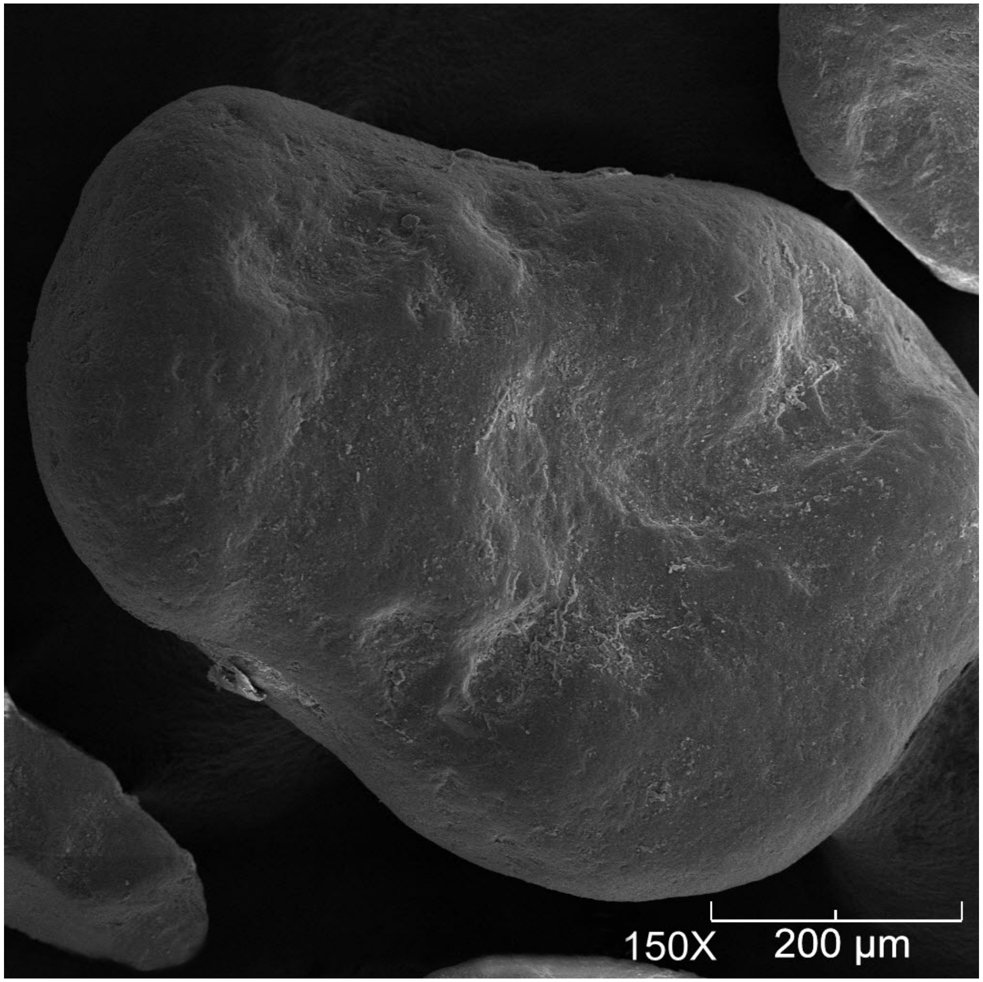
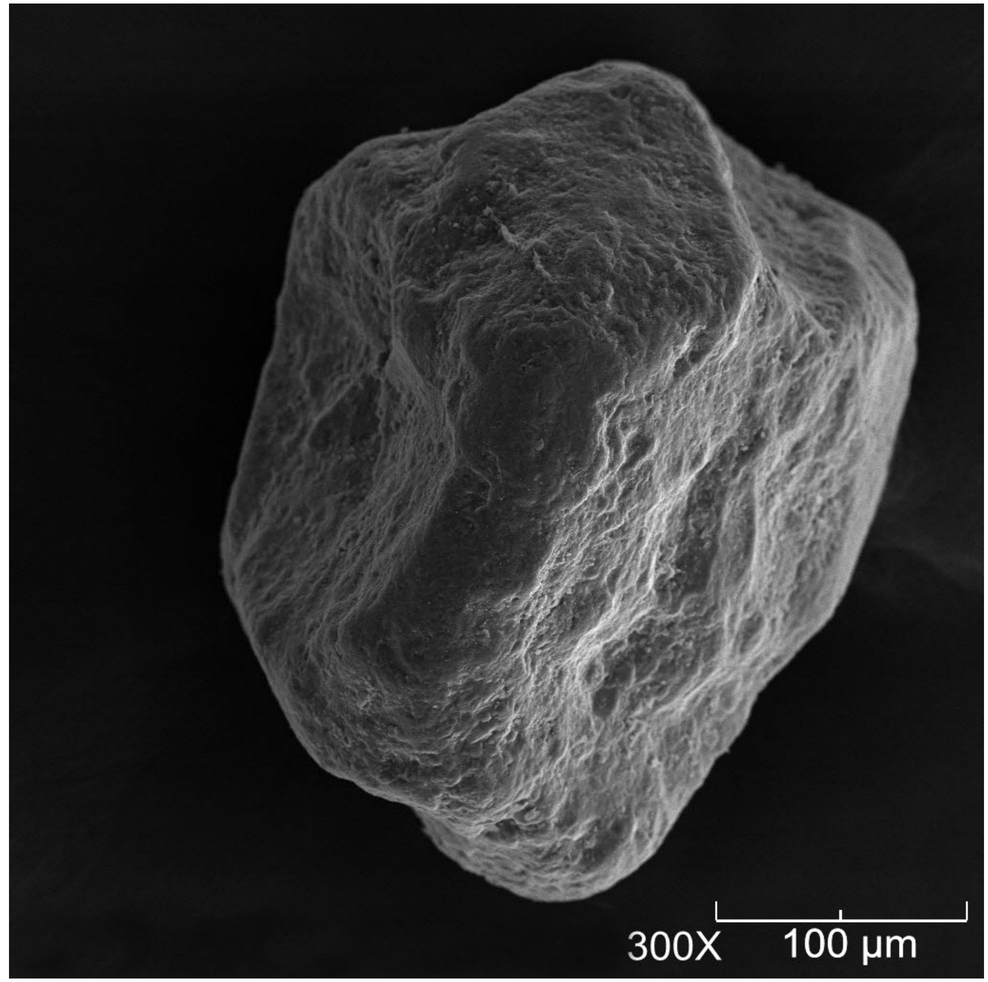


Plate III. Monolayer photomicrographs (40x) of windblown sand from dunes in McHenry County, North Dakota. Photomicrographs 1-4, 7-10, 14, 15, 22, 24 & 26 are from sand samples collected from low-relief (<10-ft, or 3m) dunes. Photomicrographs 5, 6, 11-13, 16-21, 23, 25, 27 & 28 are from sample collected from high-relief (>10-ft, or 3m) dunes.



a.



b.

Plate IV. SEM images (a. & b.) of individual quartz grains from windblown sand collected from high-relief dunes south of Towner, North Dakota (Sample DD-4). Subdued conchoidal fracturing (a.) and rounded (a.) to sub-rounded quartz grains (b.) are visible in these images.

Appendix I. Individual Sieve Diagrams for Windblown Sand Samples Collected from the Denbigh Dunes in McHenry County, North Dakota.

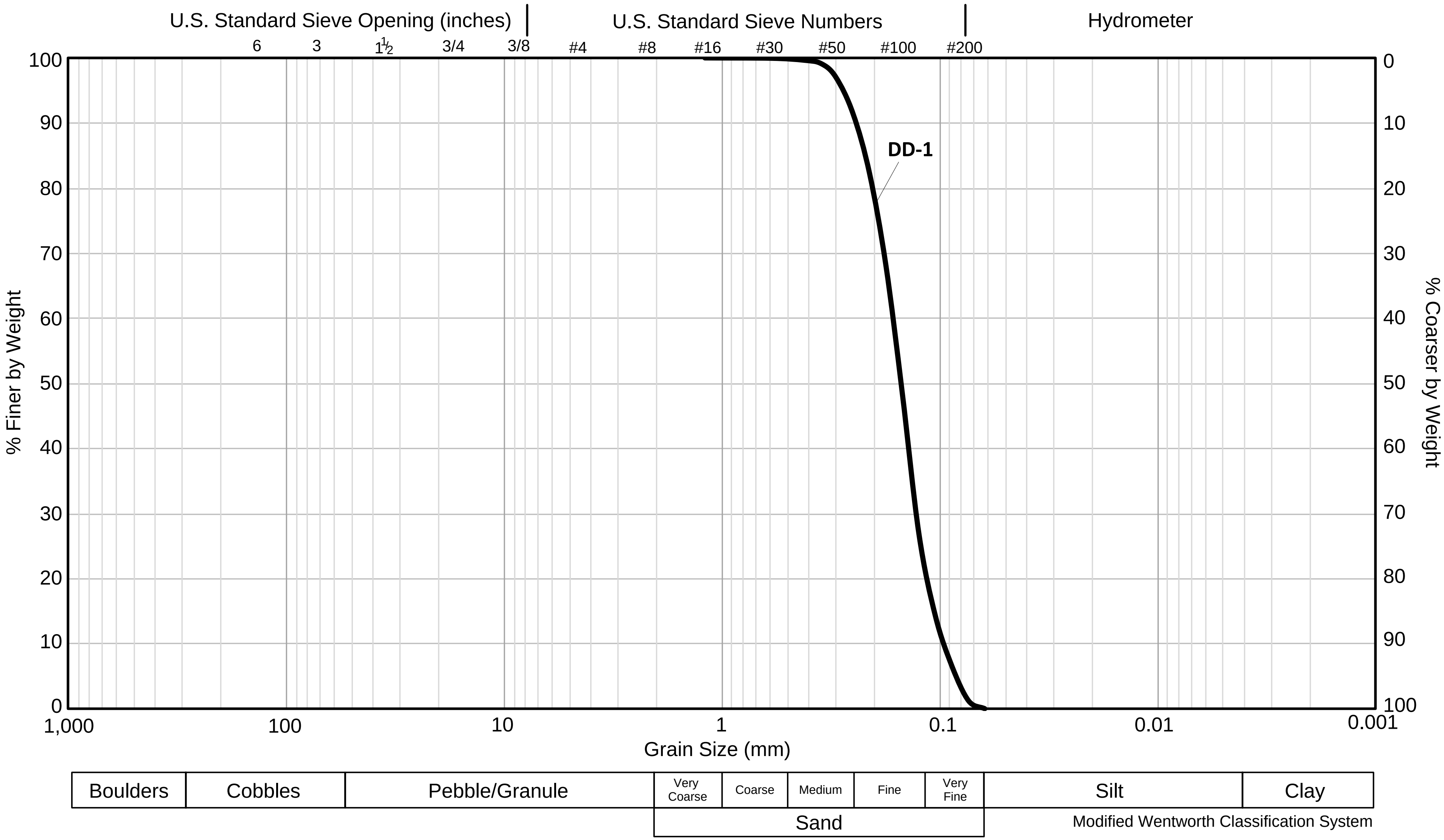


Figure A-1-1. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-1

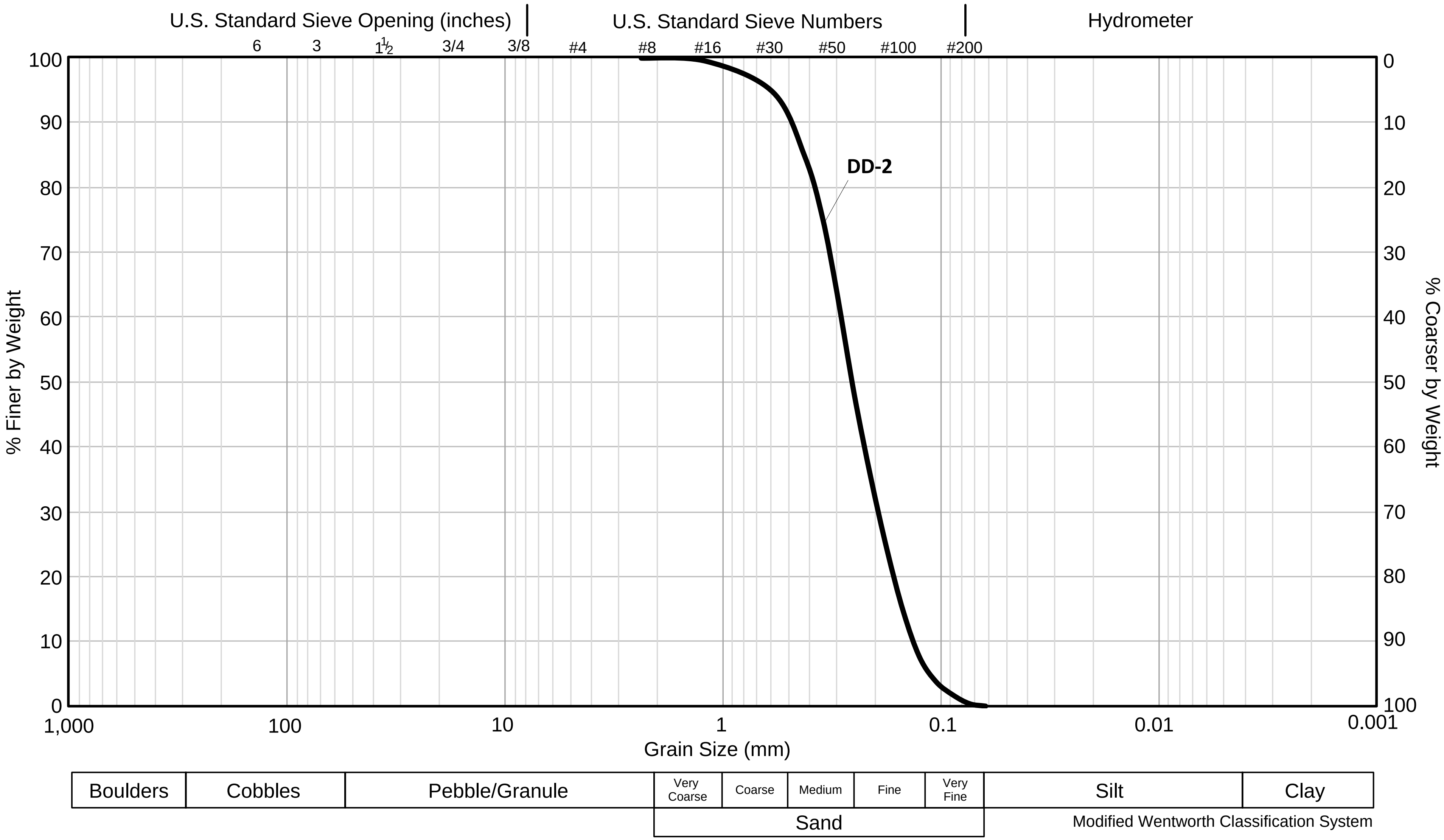


Figure A-I-2. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-2.

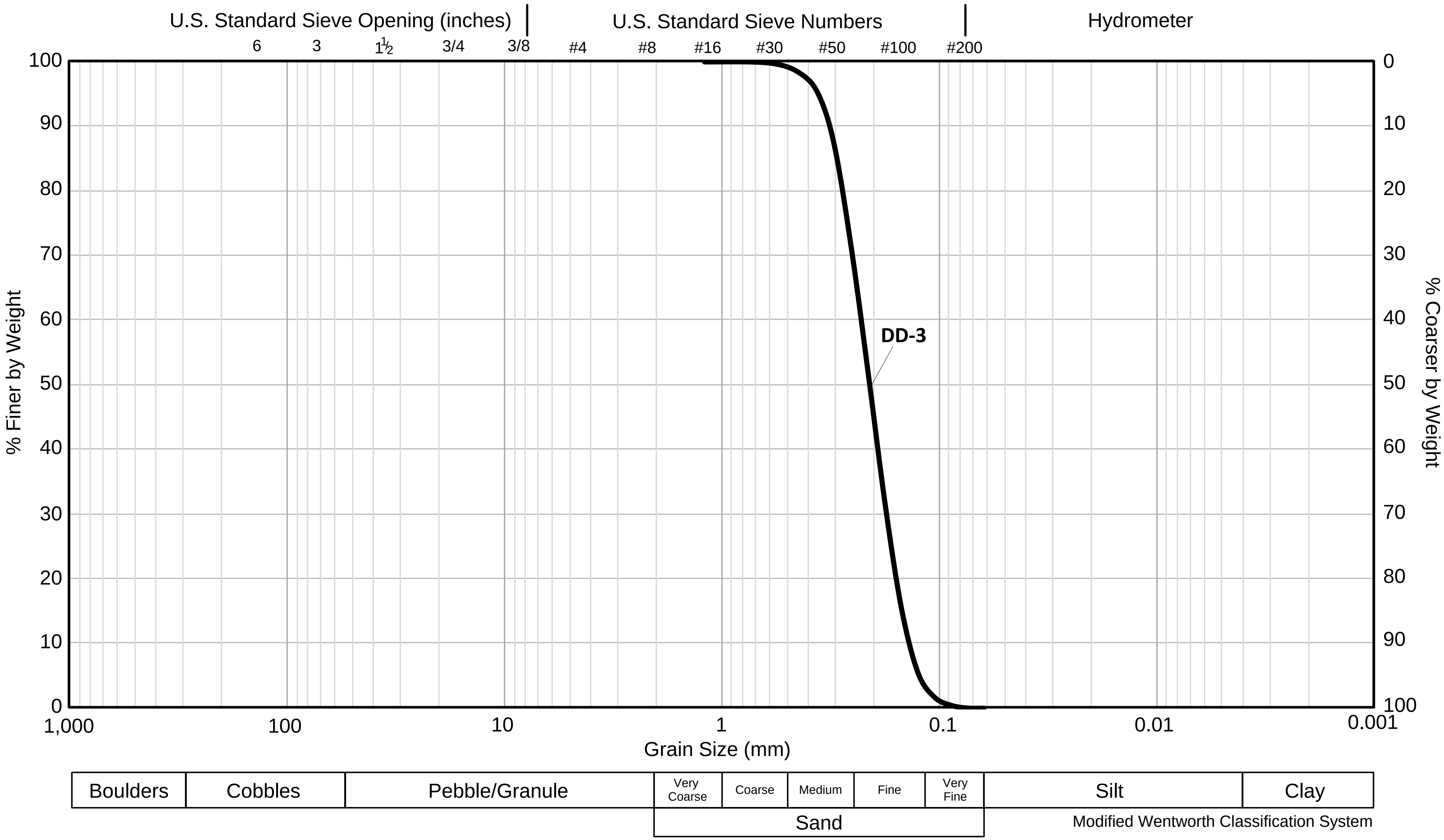
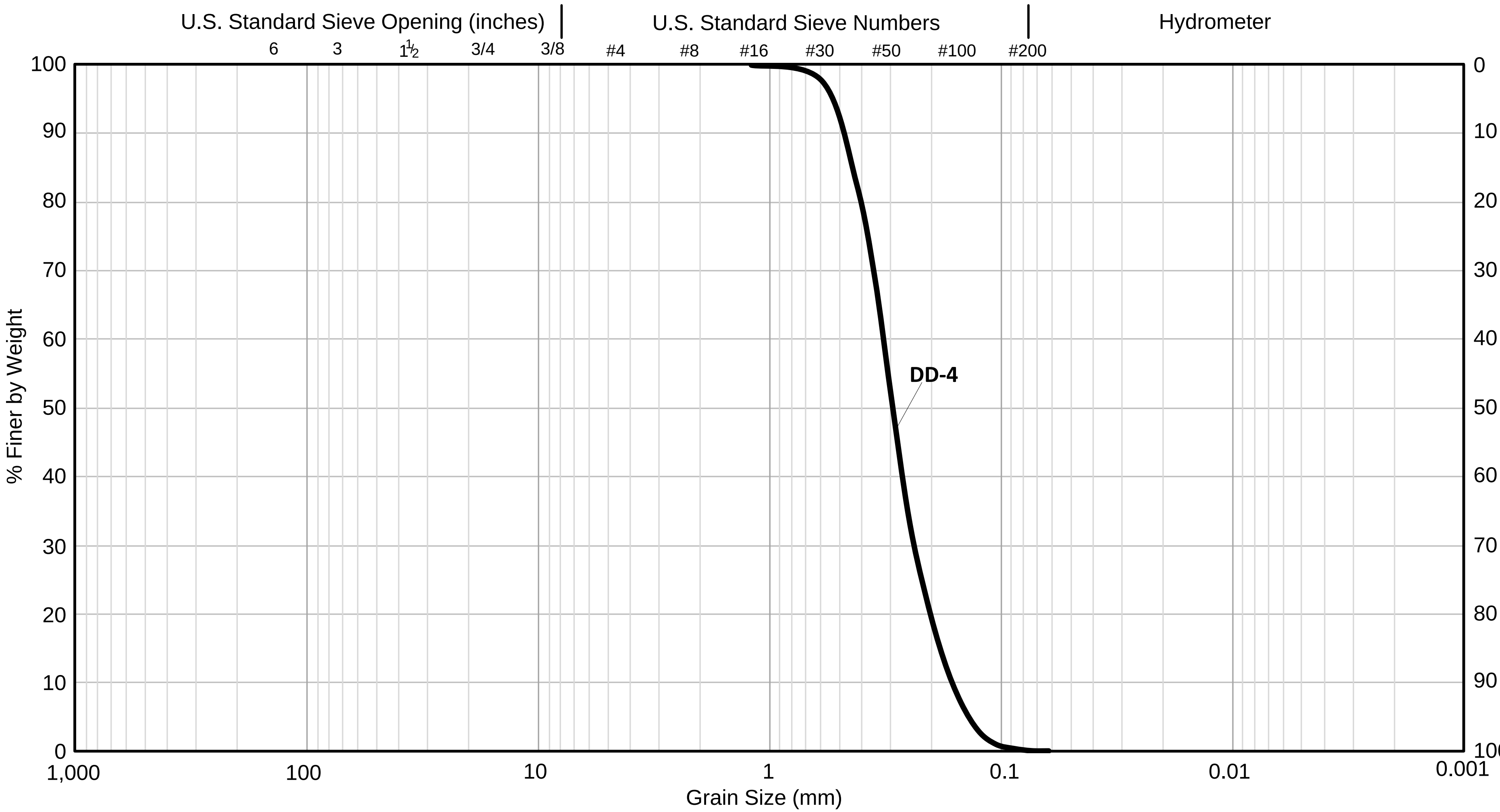


Figure A-I-3. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-3.



Boulders	Cobbles	Pebble/Granule	Very Coarse	Coarse	Medium	Fine	Very Fine	Silt	Clay
			Sand					Modified Wentworth Classification System	

Figure A-I-4. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-4.

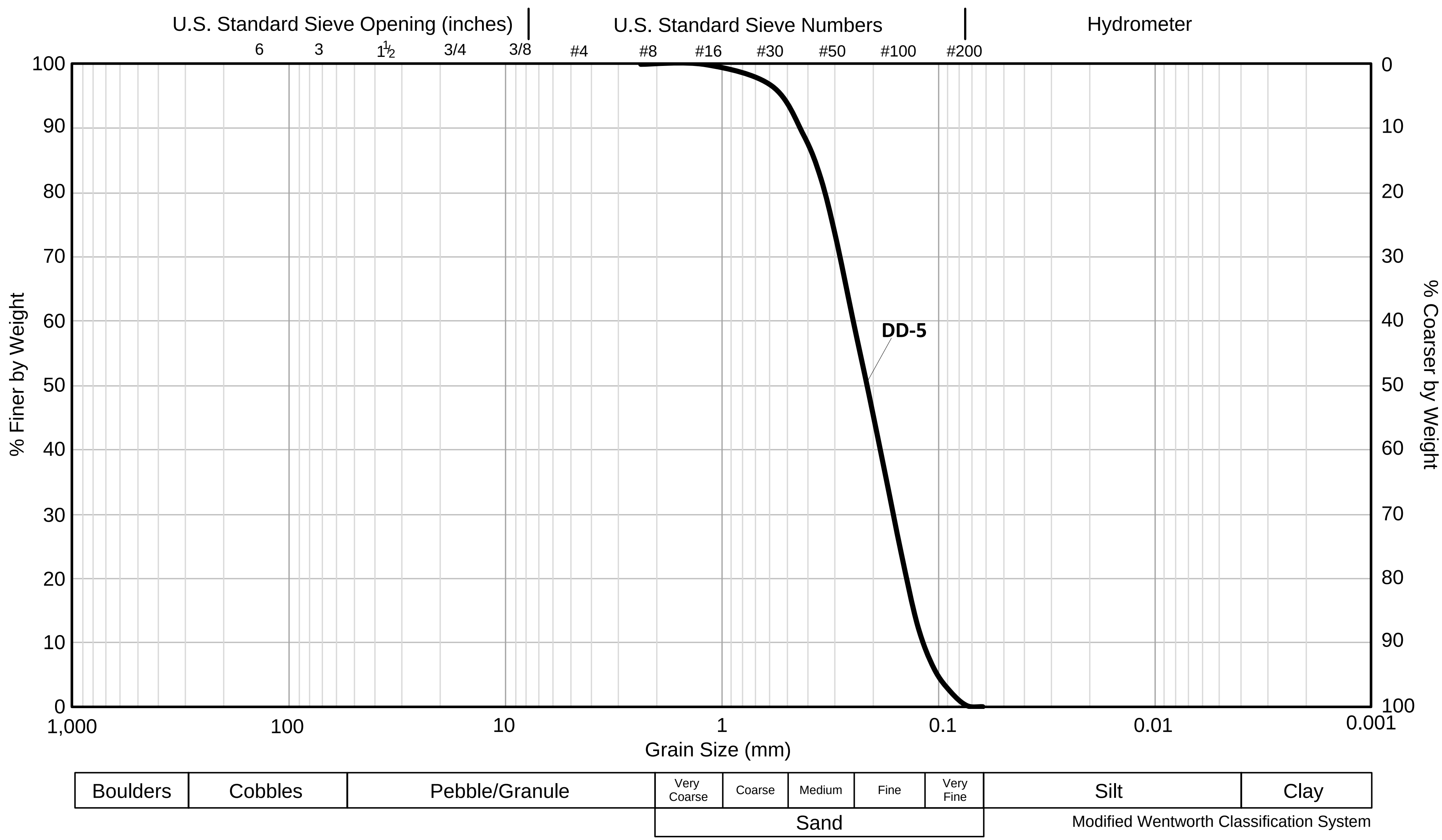


Figure A-I-5. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-5.

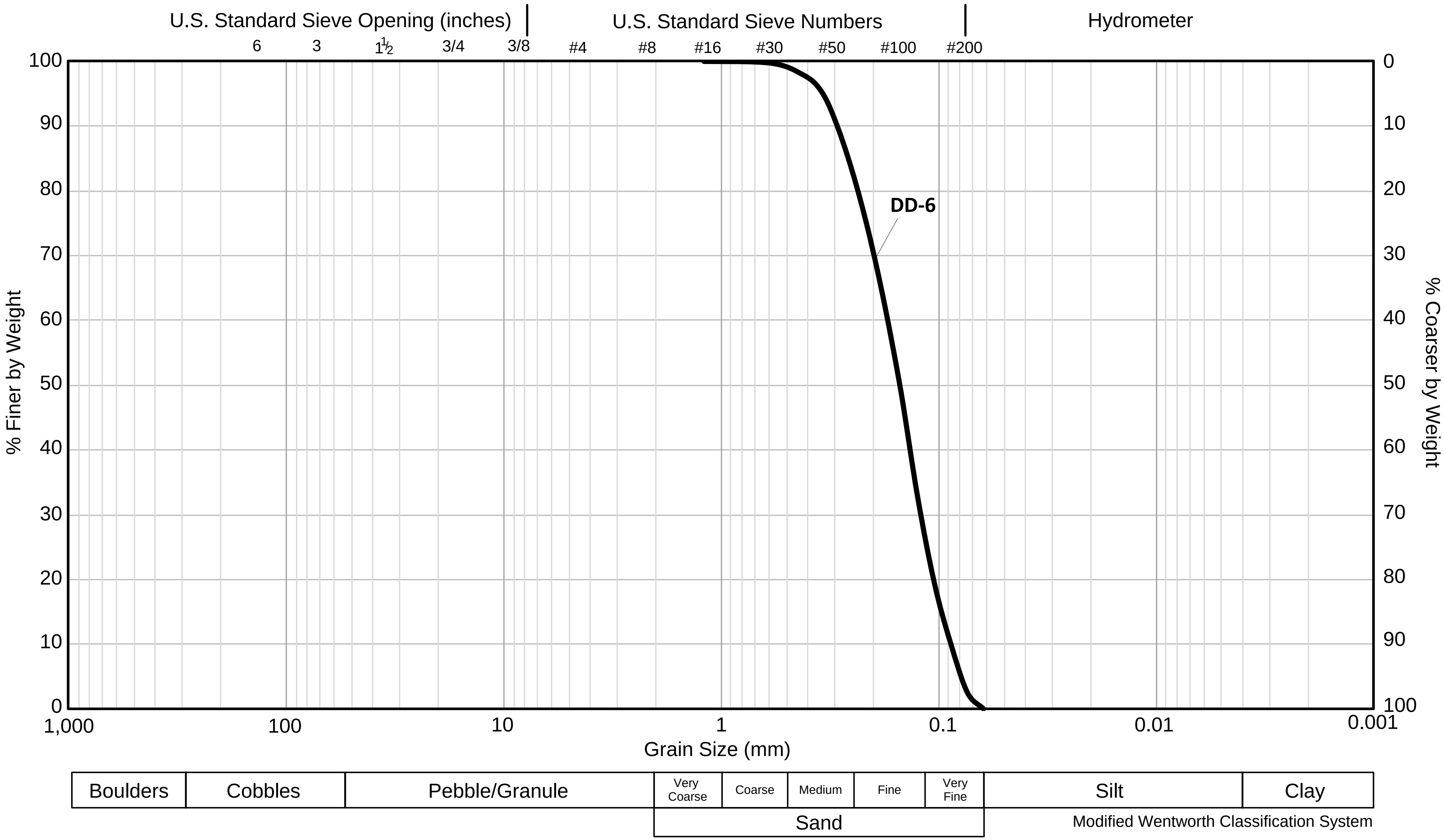


Figure A-I-6. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-6.

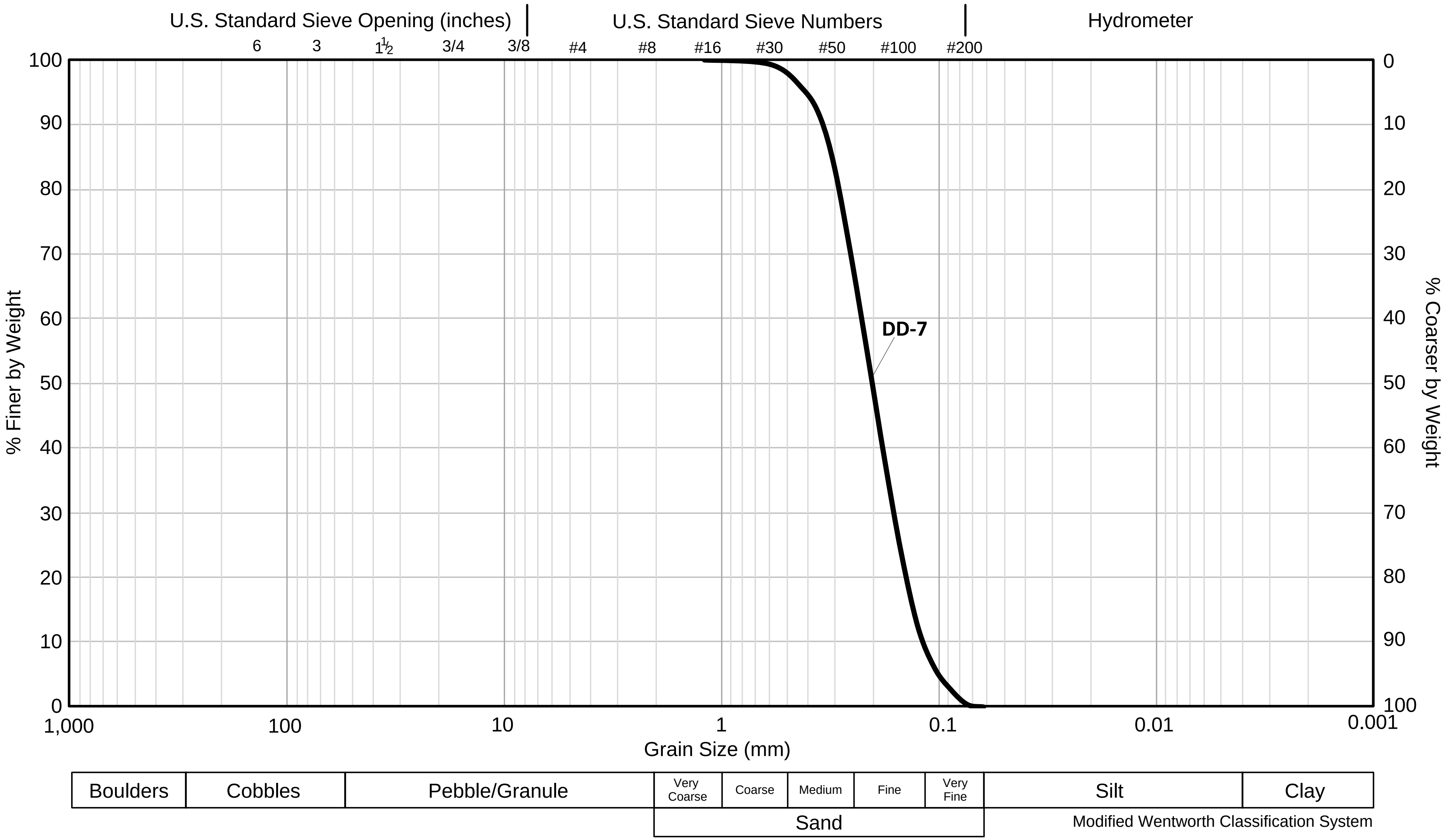


Figure A-I-7. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-7.

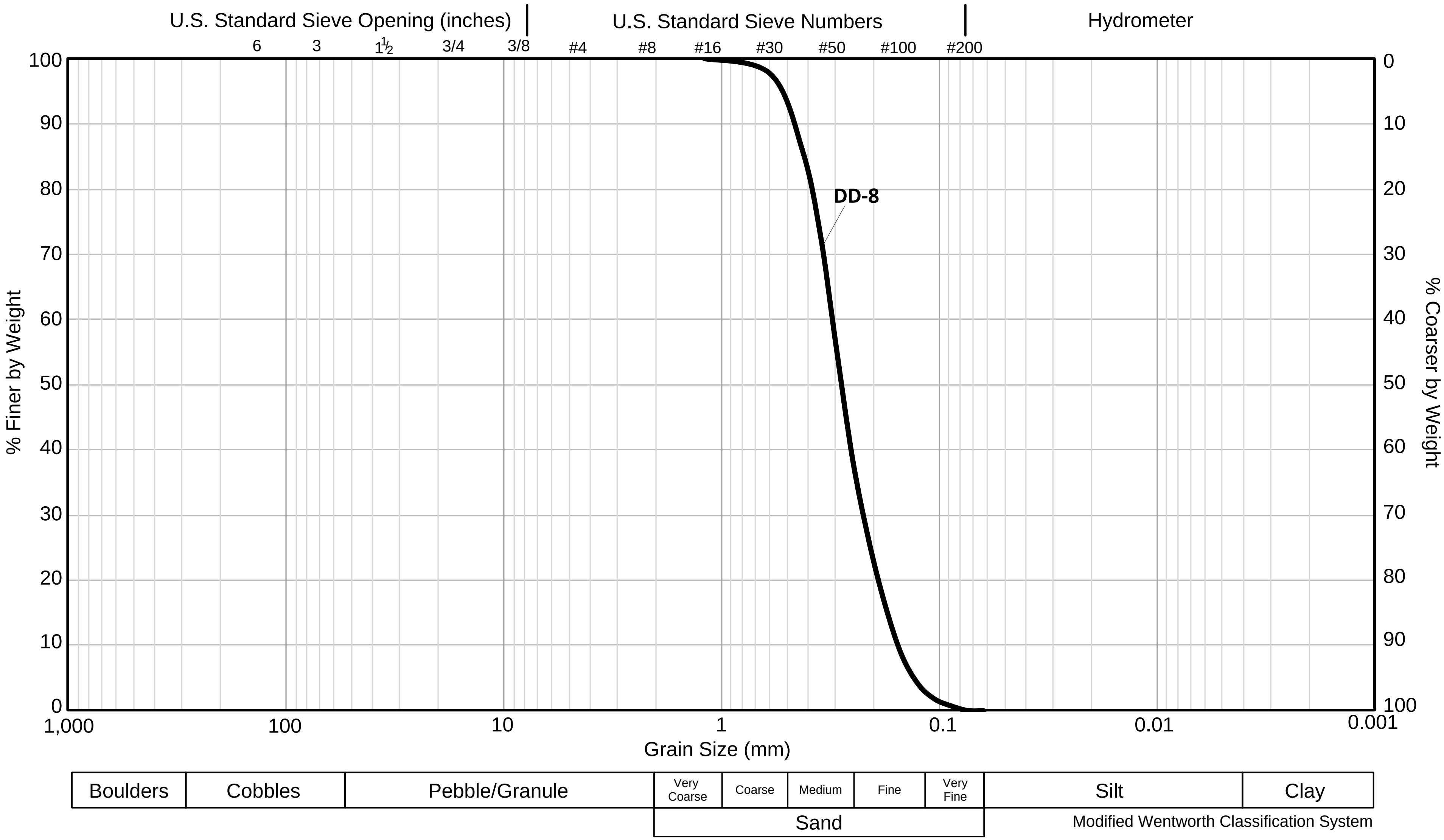


Figure A-I-8. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-8.

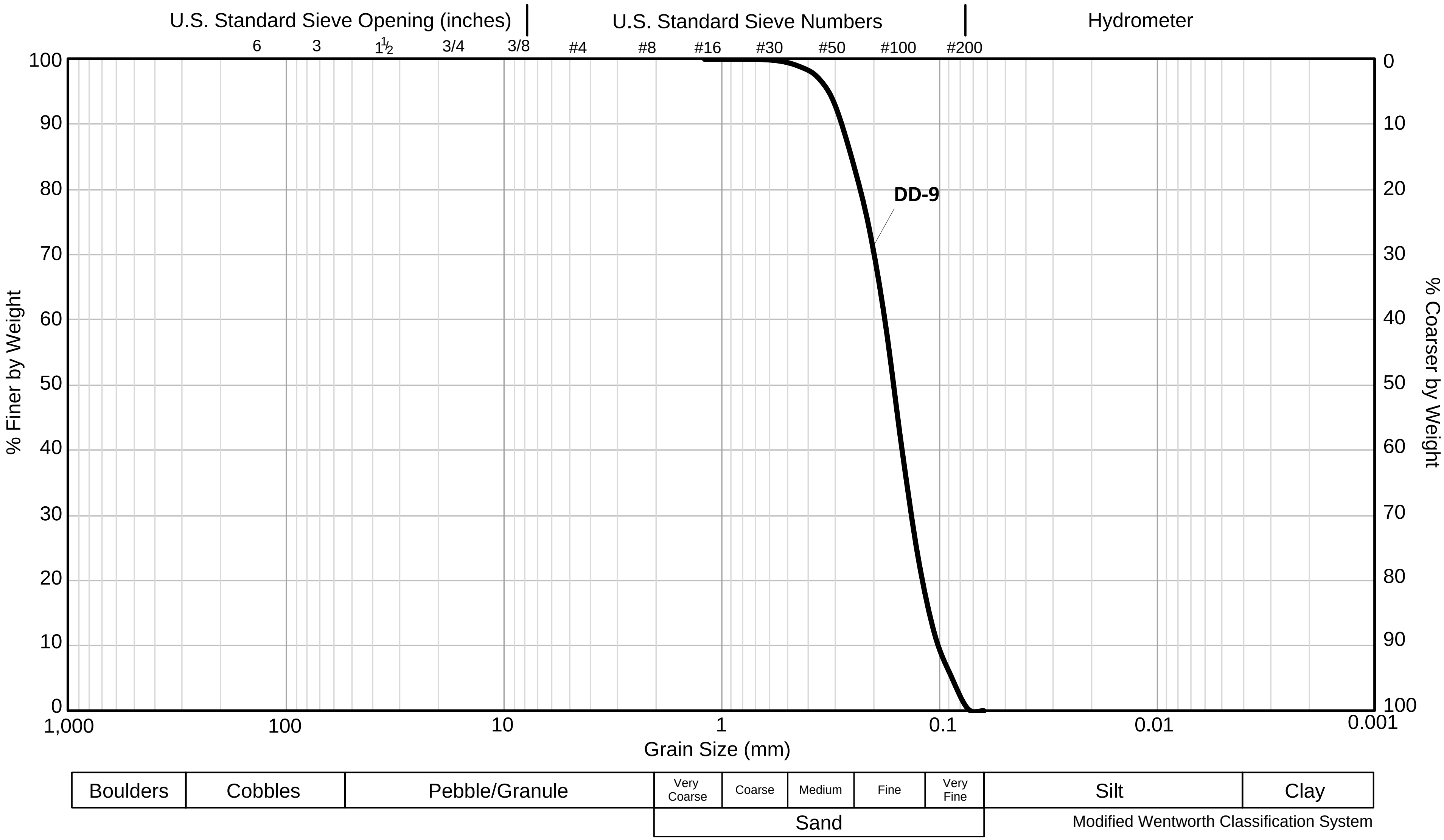


Figure A-I-9. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-9.

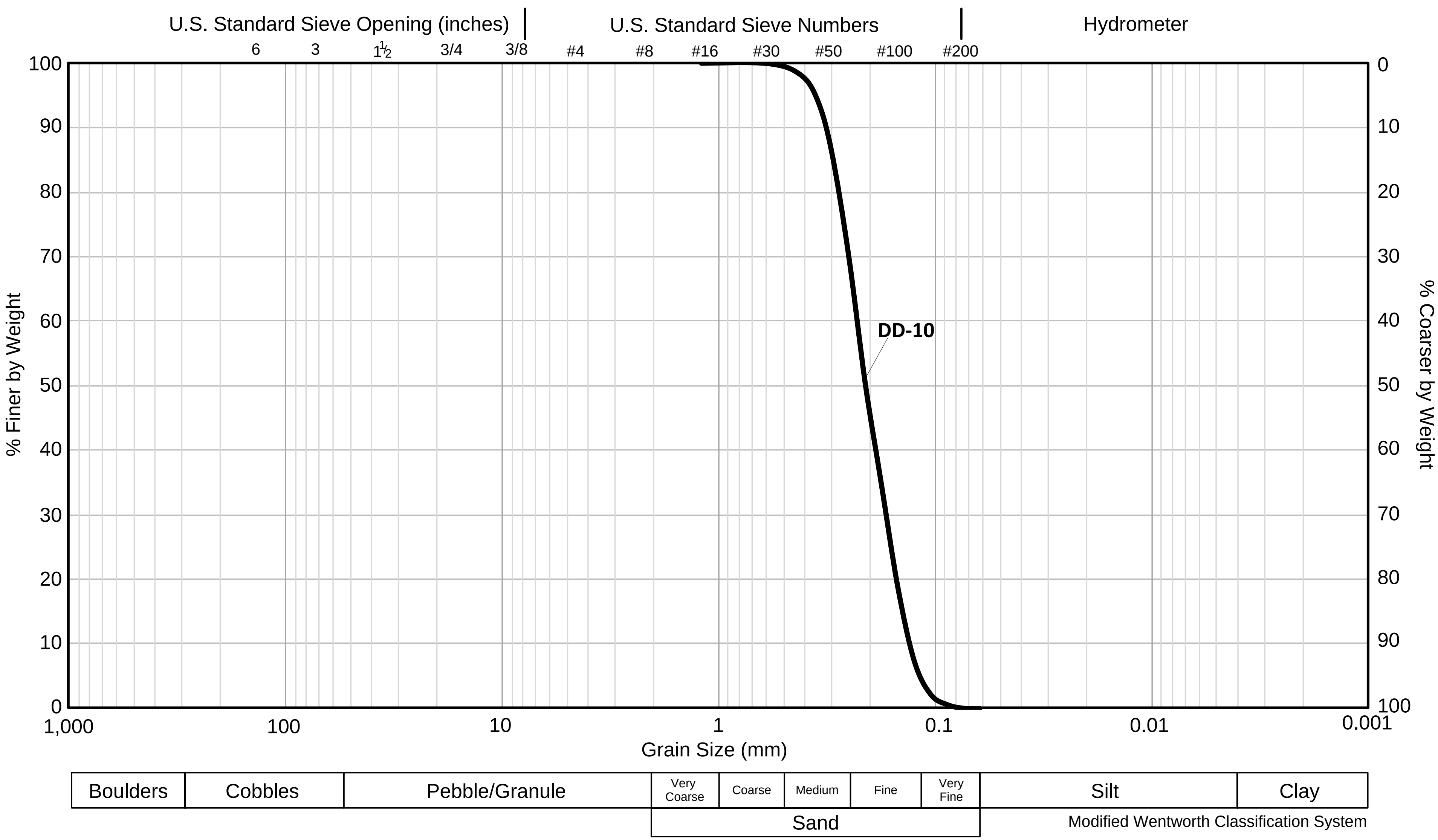


Figure A-I-10. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-10.

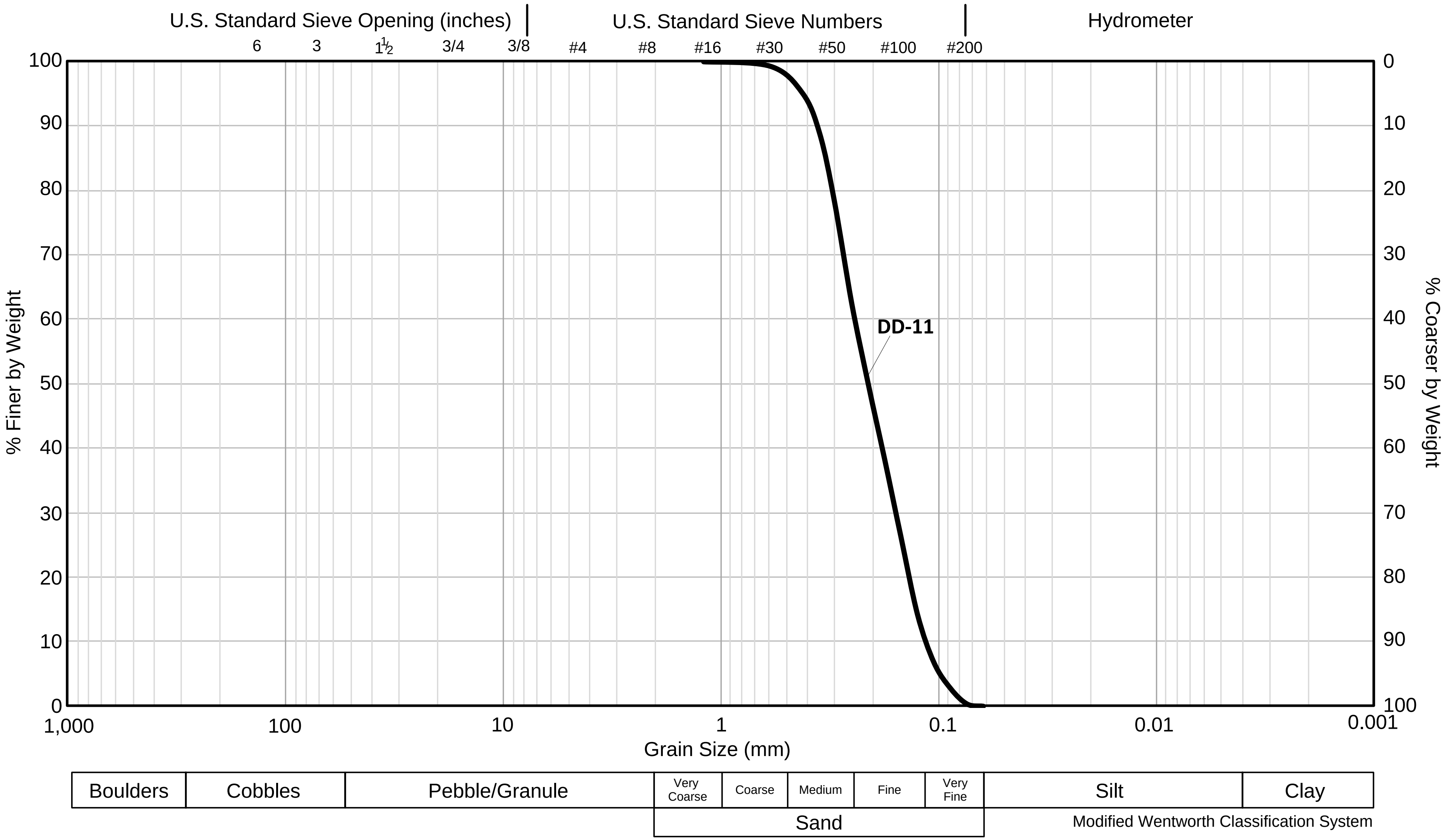


Figure A-I-11. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-11.

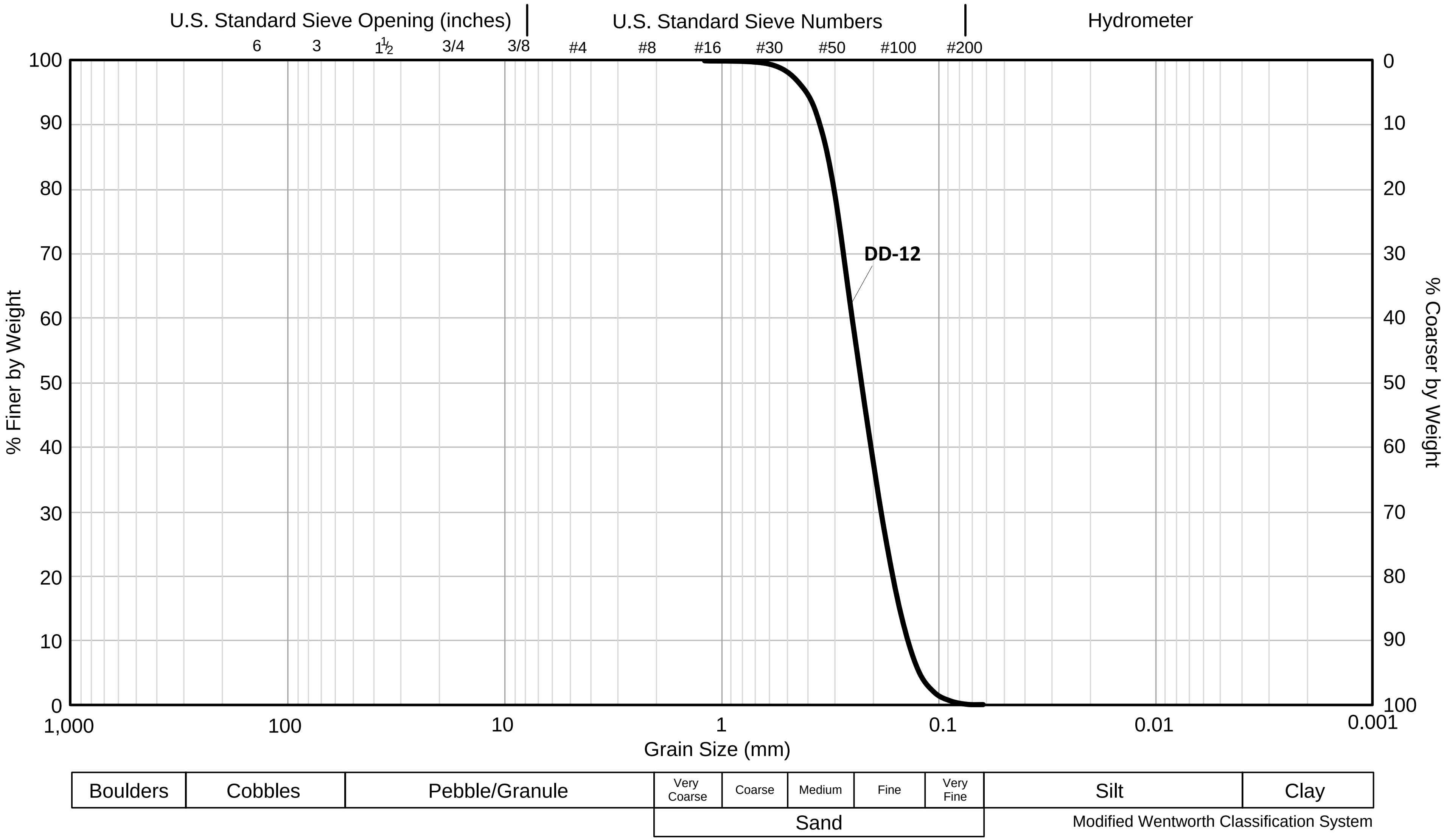


Figure A-I-12. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-12.

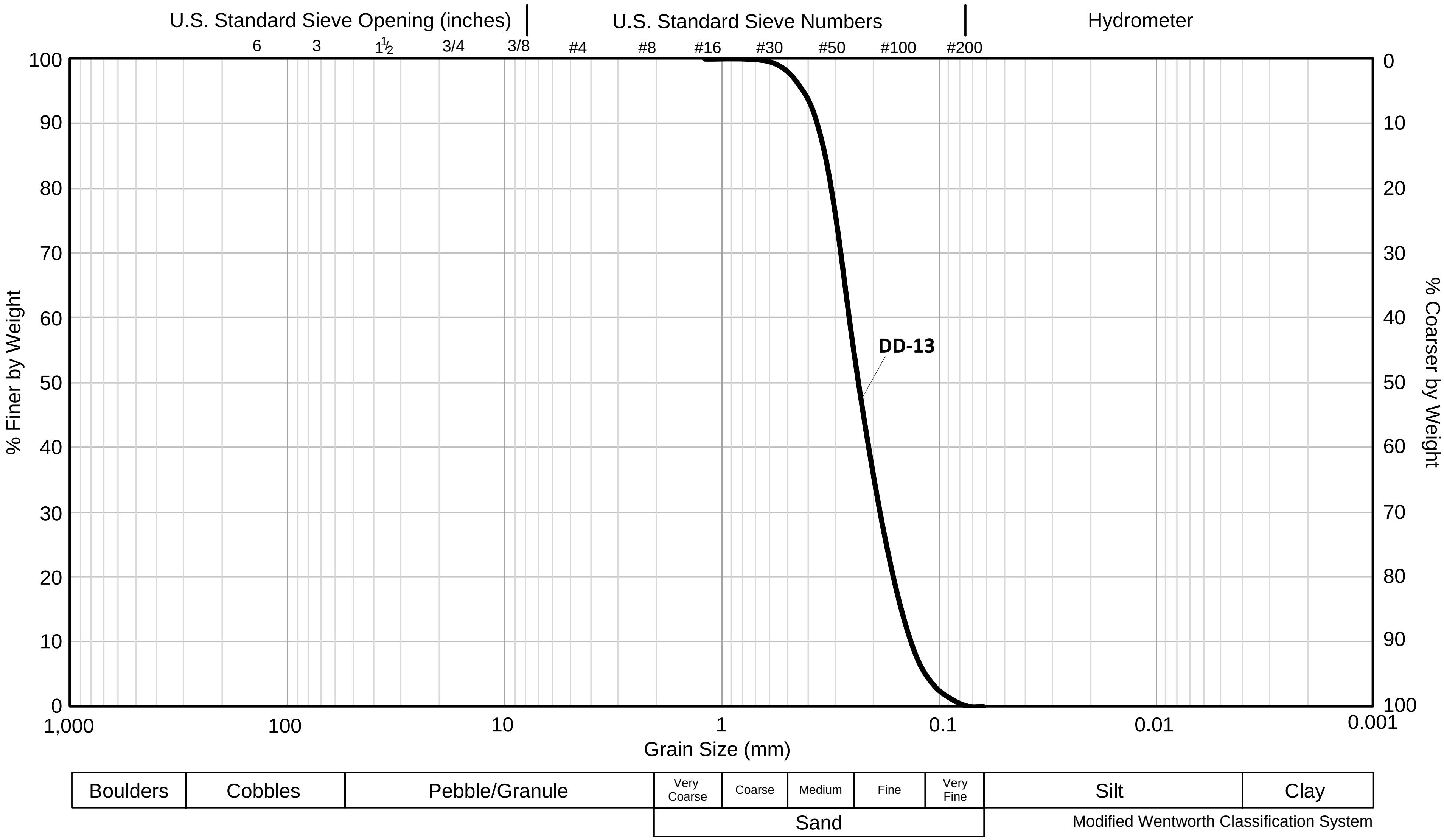


Figure A-I-13. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-13.

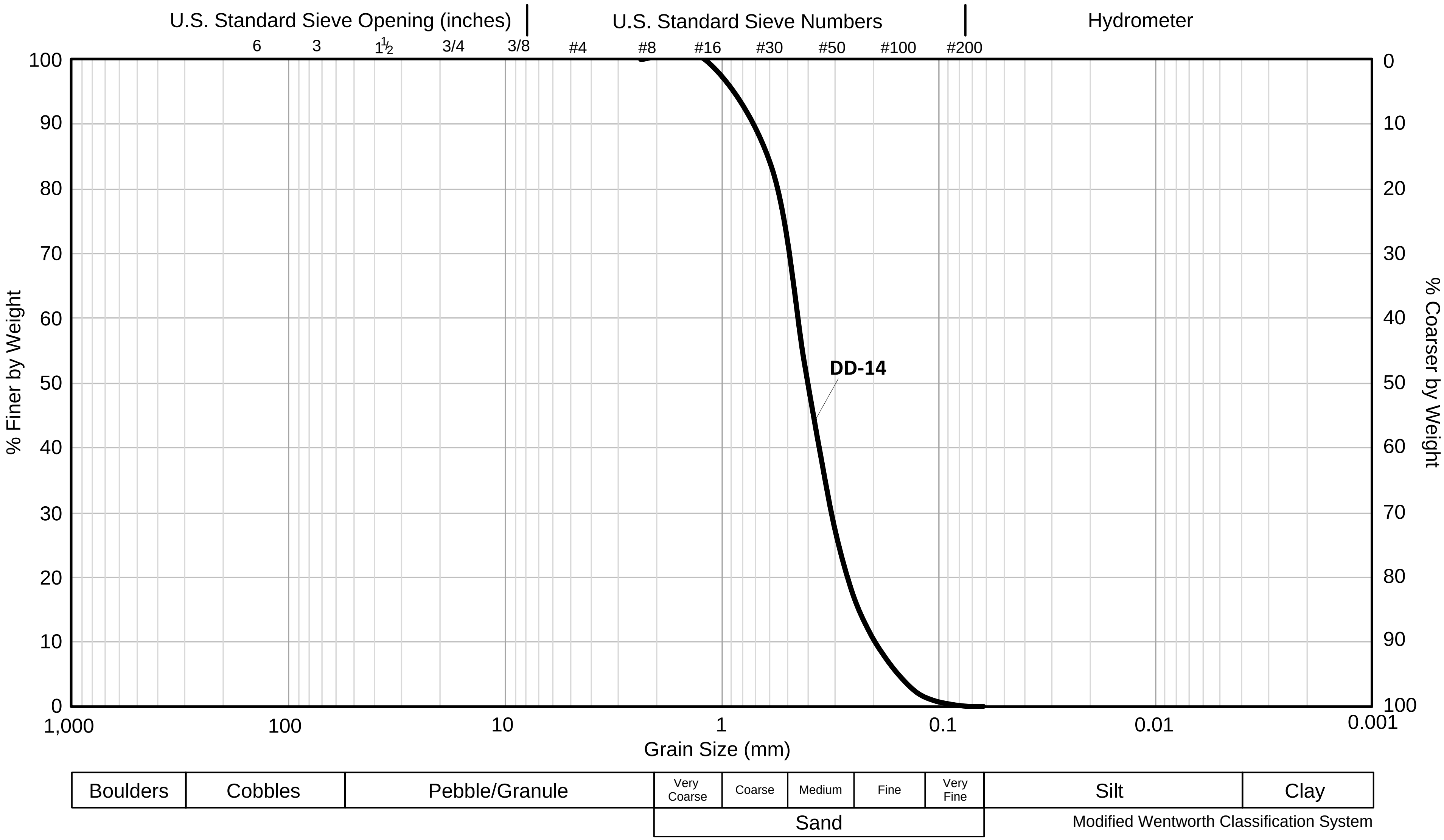


Figure A-I-14. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-14.

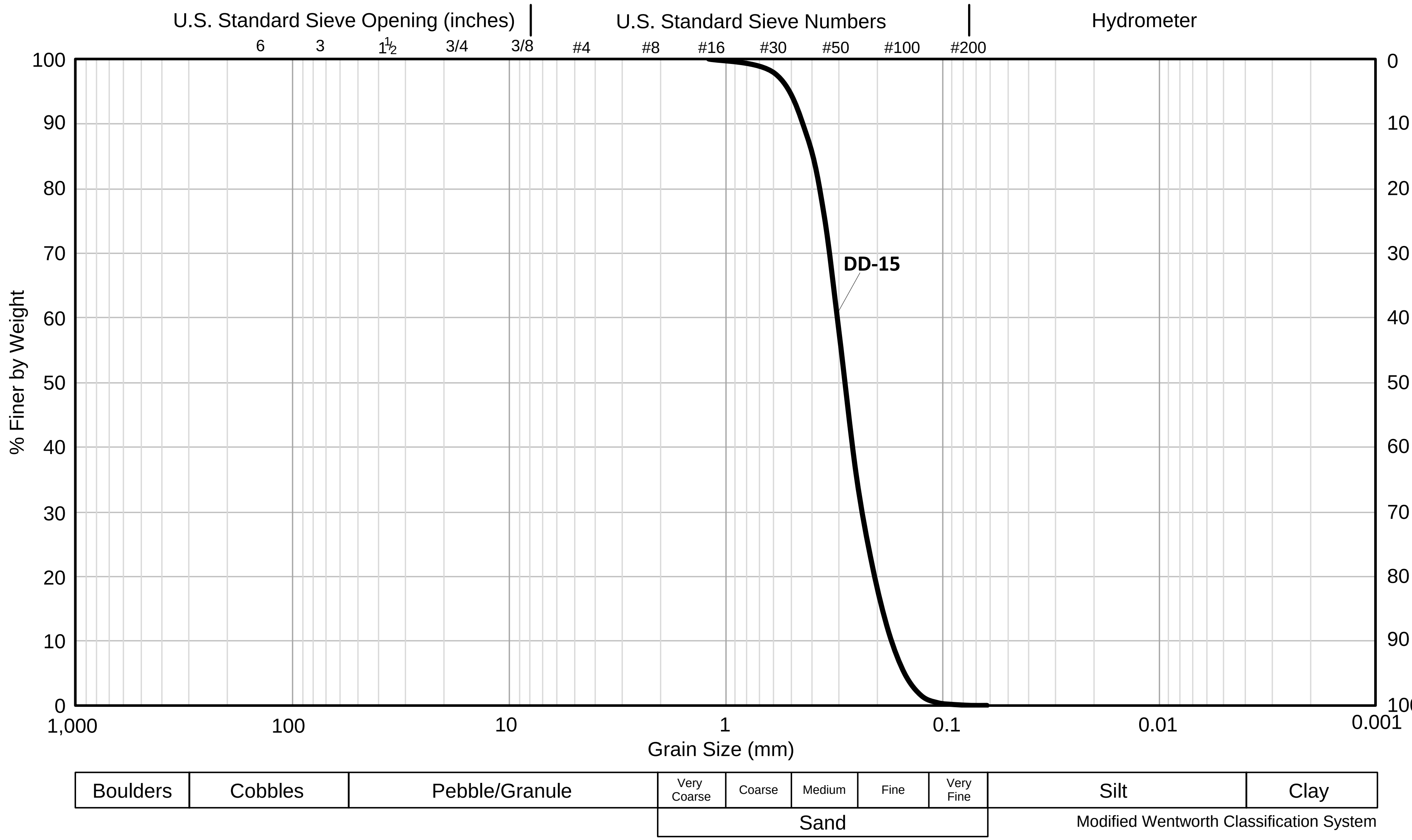


Figure A-I-15. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-15.

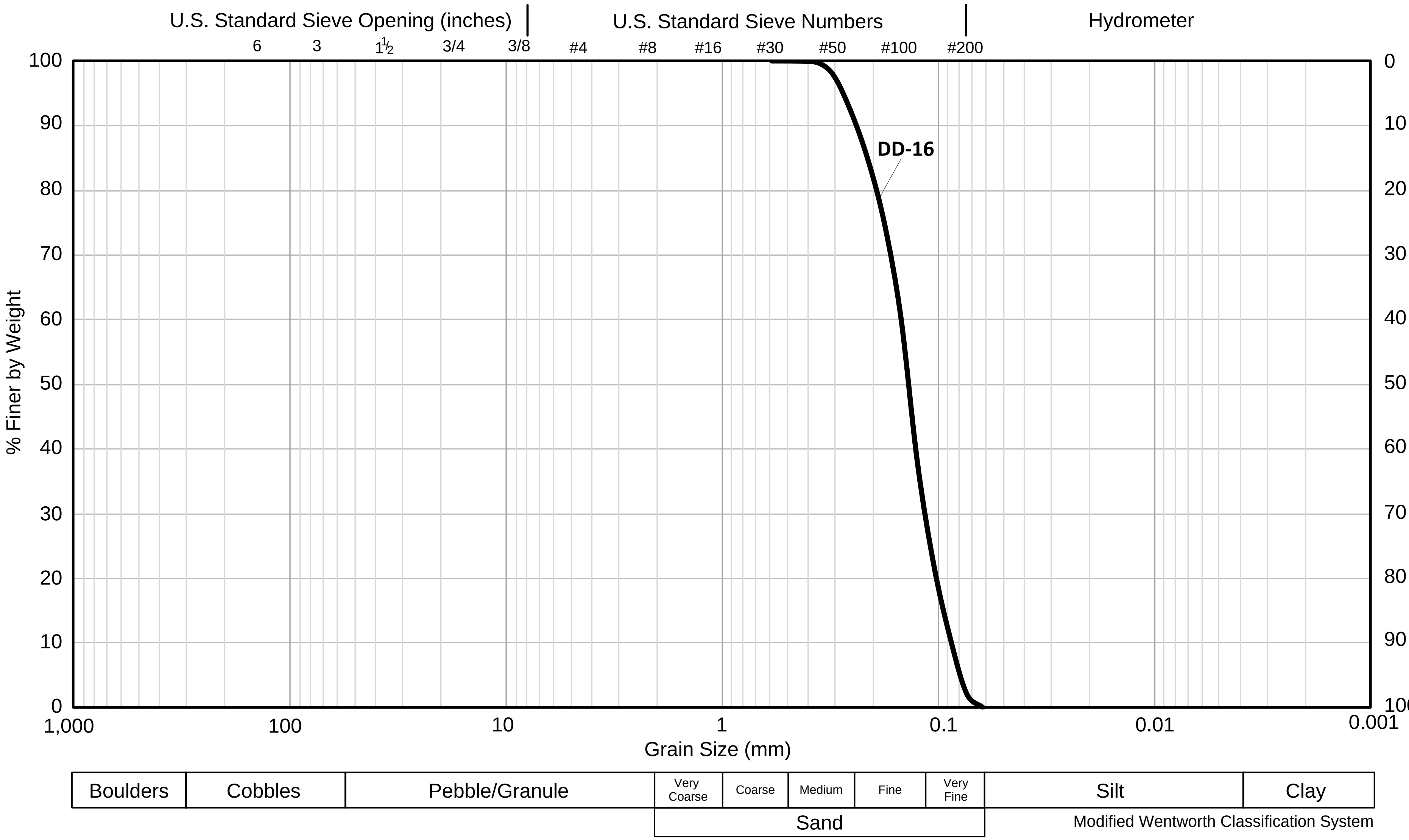


Figure A-I-16. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-16.

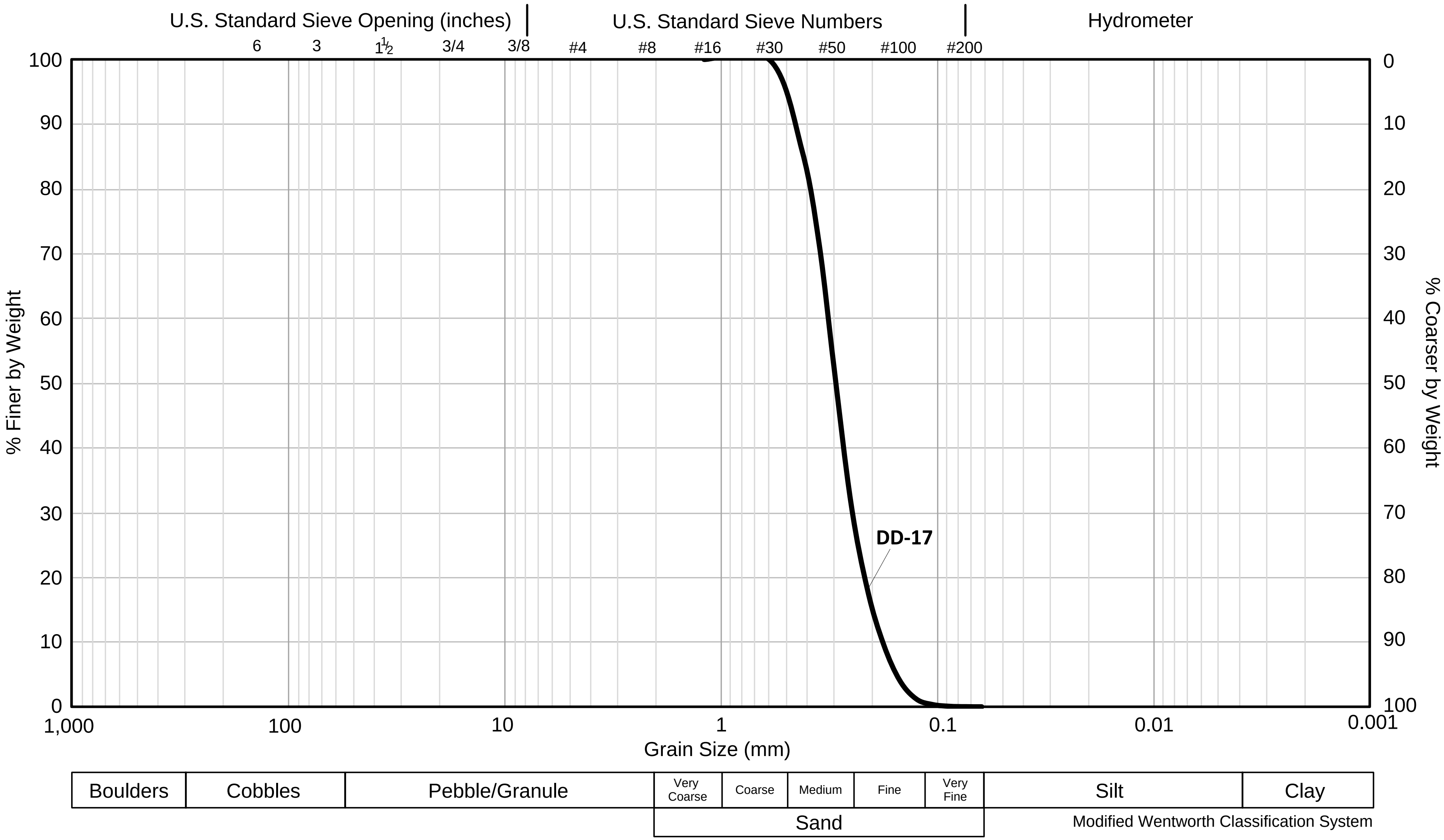


Figure A-I-17. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-17.

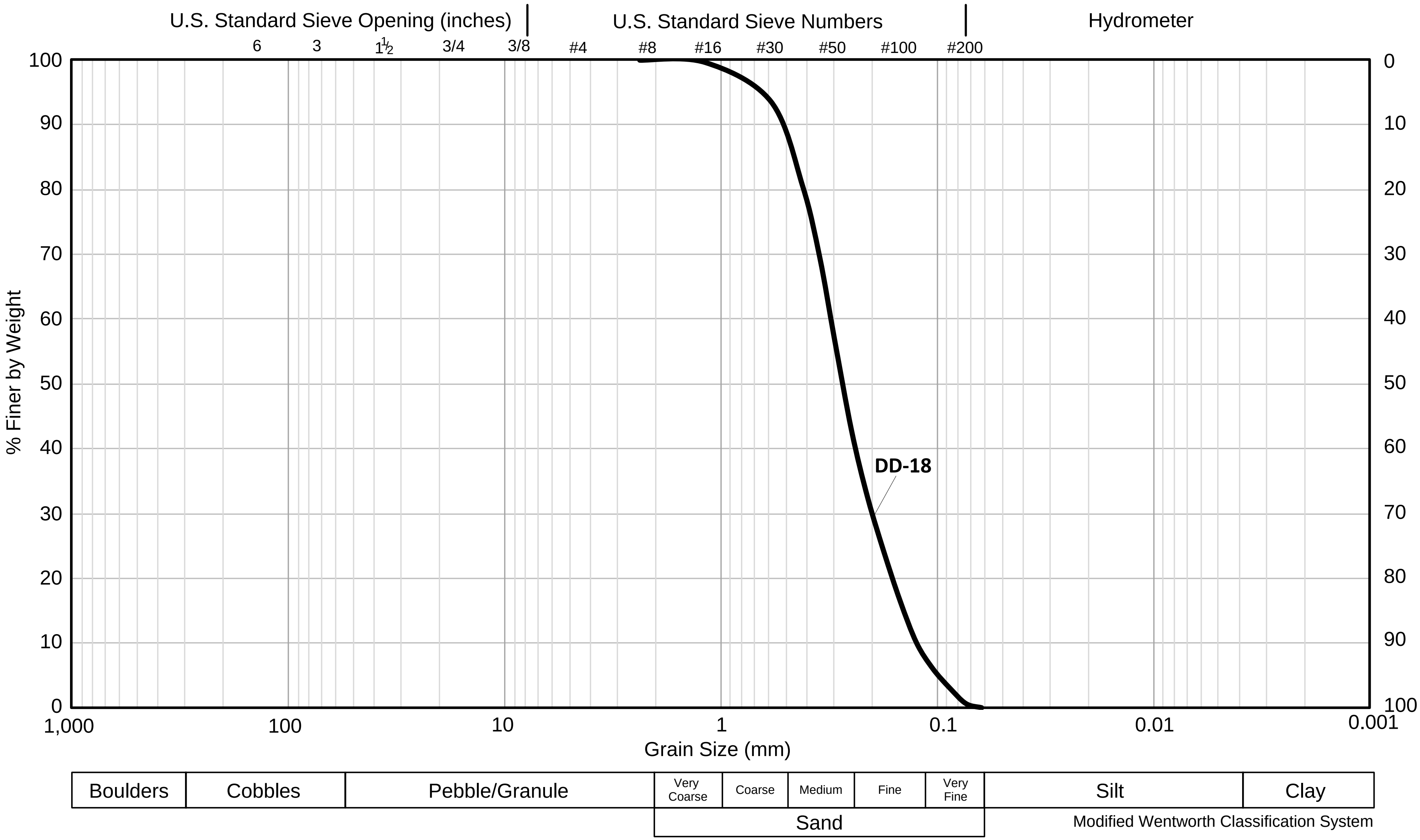


Figure A-I-18. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-18.

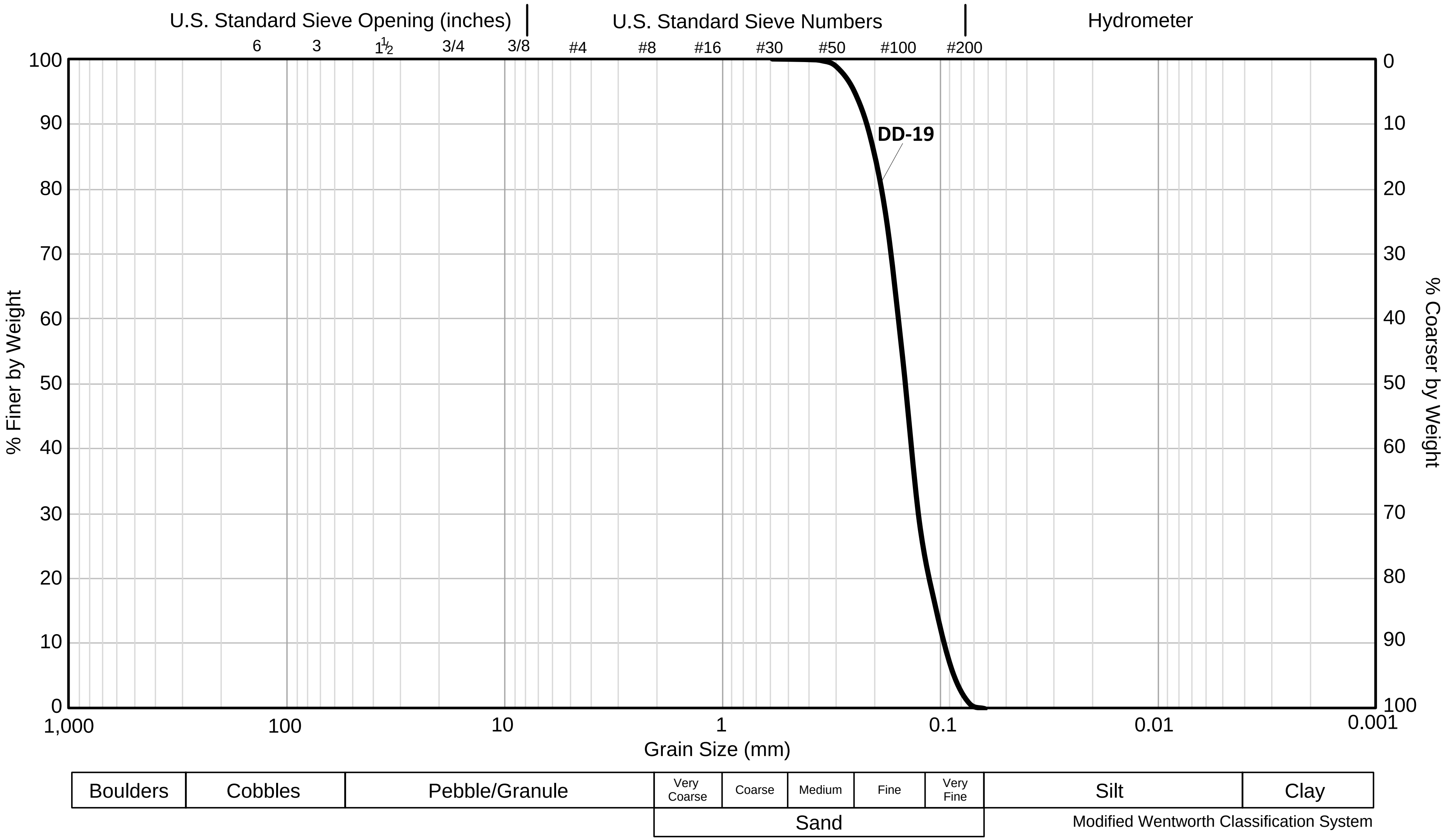


Figure A-I-19. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-19.

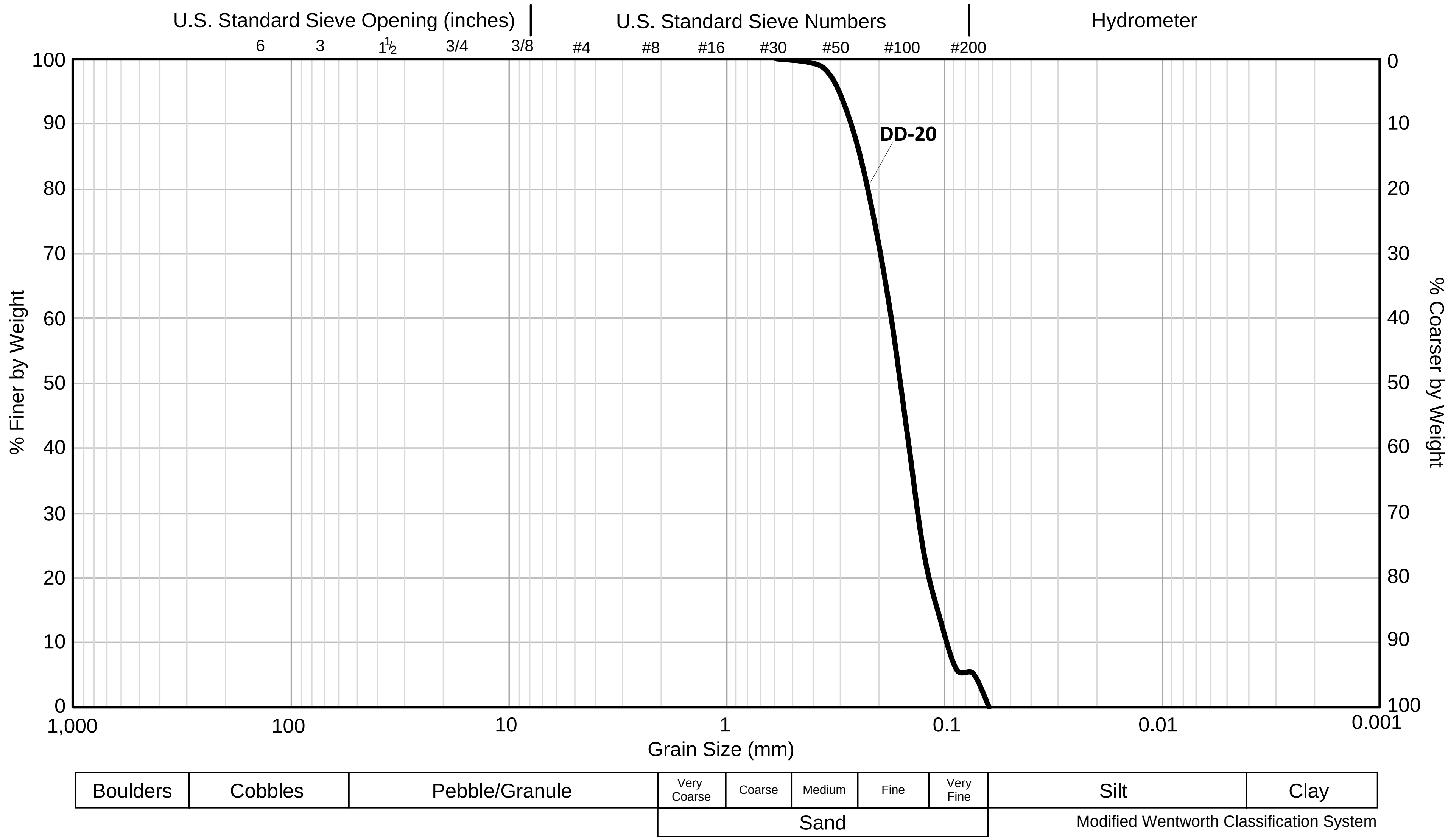


Figure A-I-20. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-20.

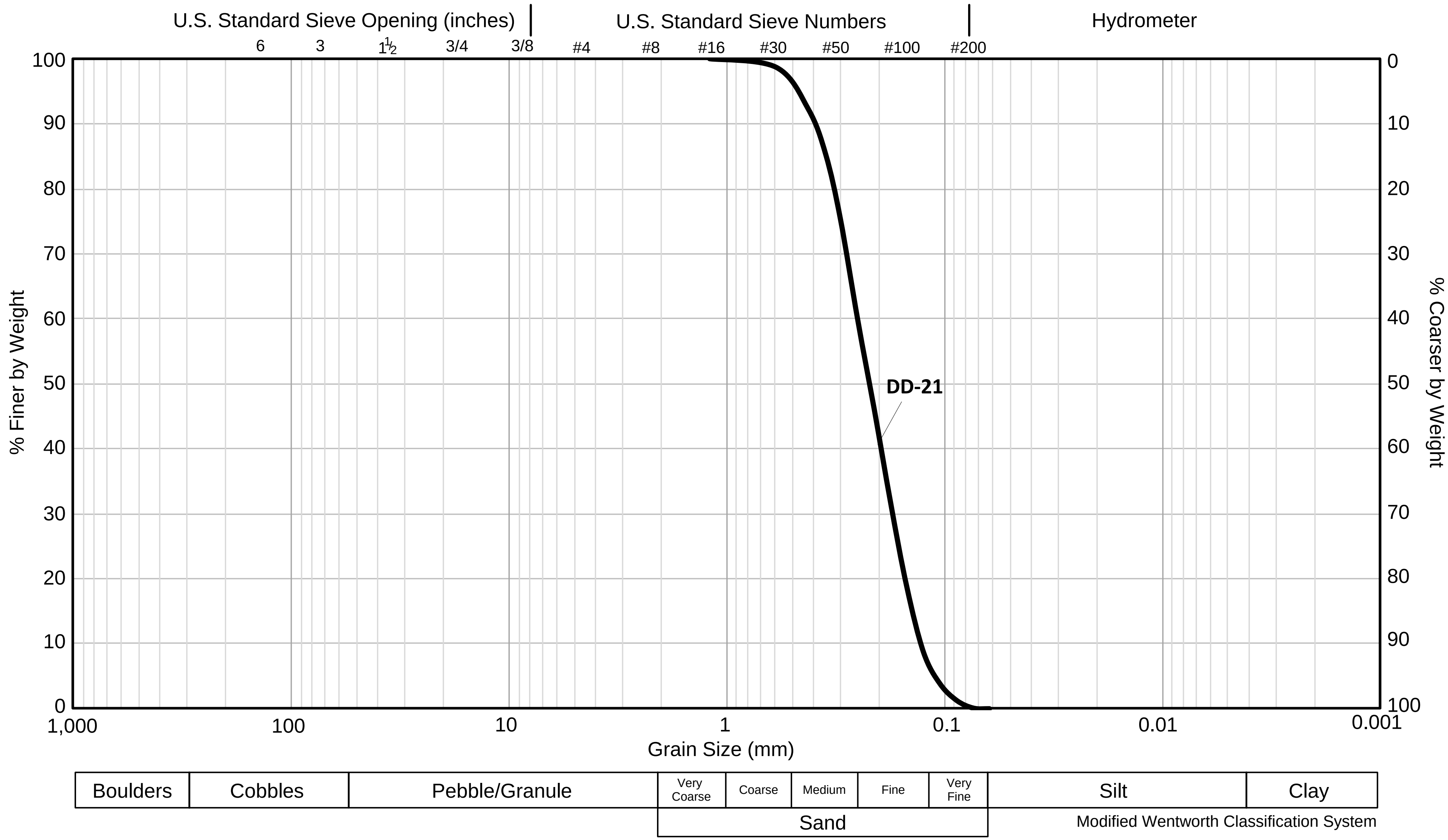


Figure A-I-21. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-21.

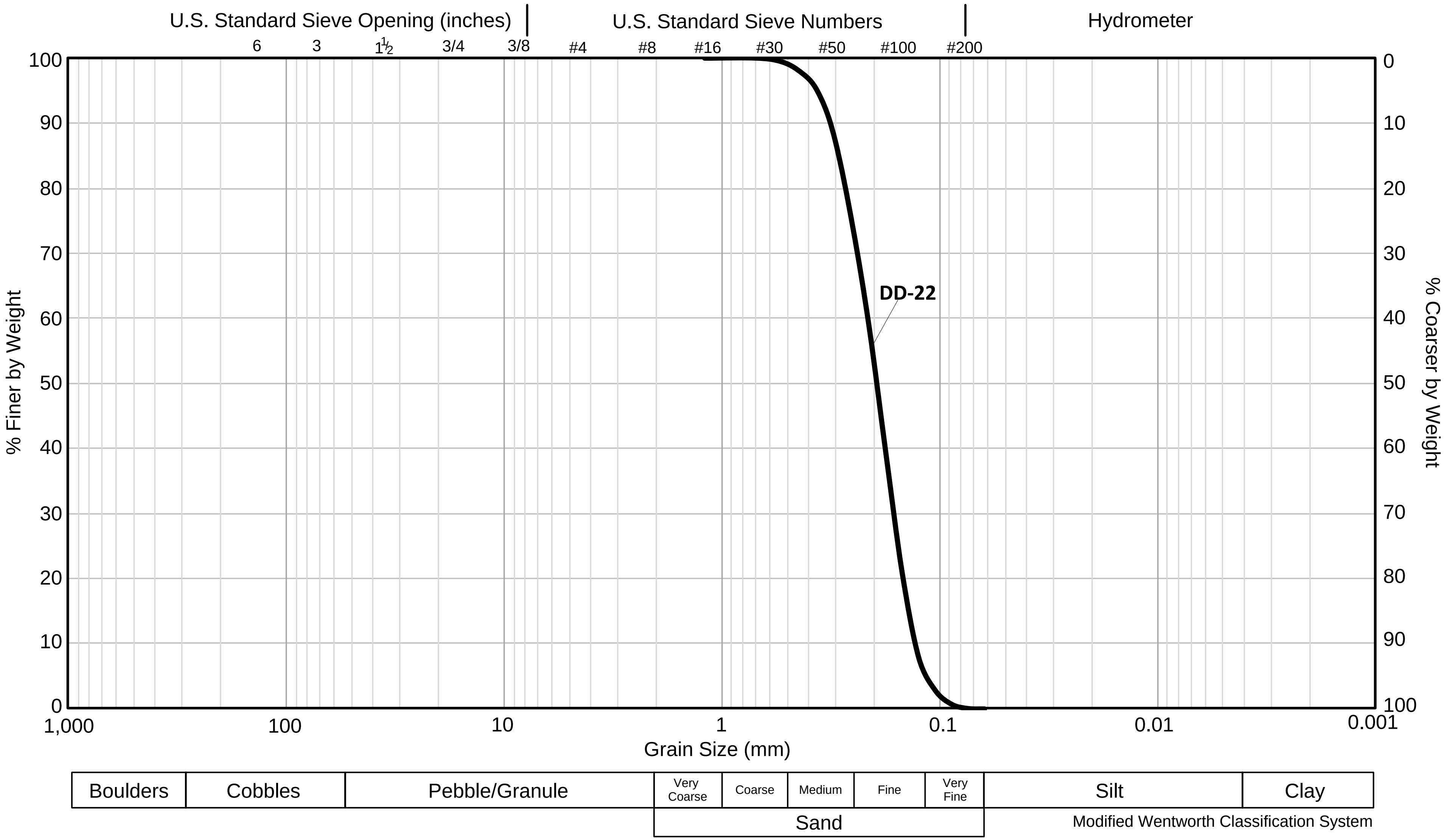


Figure A-I-22. Grain-size distribution diagram (mechanical sieve analysis) for Sample No. DD-22.

Appendix II - XRD Mineralogical Analysis of Windblown Sand from the Denbigh Dunes in McHenry County, North Dakota

Introduction

Sampling of windblown sand from the Denbigh Dunes in McHenry County, North Dakota was completed during the 2019 field season. The sampling was 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 28 samples from 22 locations were collected from low and high-relief dune fields across McHenry County and submitted to Lonquist Frac Sand Services in Austin, Texas for X-ray diffraction (XRD) mineralogical analysis.

XRD-Methodology

The analytical patterns shown in the phase diagrams of Figures A-II-1 through A-II-28 included in this appendix represent the identified mineralogical phases (Table 1). 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 mineralogical quantification (Table 2). It should be noted that these sands were found to be essentially devoid of carbonate minerals in the washed sample size classes tested.

Table 1. Summary Denbigh Windblown Sand Mineralogy by XRD Analysis[1]

Major	Moderate	Minor	Comments
Quartz	*Feldspars*[2] *Albite* *Microcline*	*Clinochlore* *Clays*[2] *Illite* *Indialite* *Magnetite*	*Glycolation and specific orientation procedures not performed for clay mineralogy*

[1] *Washed (Selected Size Class) Sample Analysis.*

[2] *Undifferentiated.*

Table 2. Denbigh Windblown Sand Mineralogy by XRD Analysis[3]

Sample No.	Quartz	Feldspars[4]	Clays[4]	Carbonates	Clinochlore	Indialite	Magnetite
DD-1 (70/140)	82.1	17.9	0.0	--	--	--	--
DD-2 (40/70)	83.2	16.9	0.0	--	--	--	--
DD-3 (40/70)	81.4	18.6	0.0	--	--	--	--
DD-3 (70/140)	79.7	20.3	0.0	--	--	--	--
DD-4 (40/70)	81.8	17.4	1.9	--	--	--	--
DD-4 (70/140)	79.2	17.4	3.4	--	--	--	--
DD-5 (70/140)	74.7	25.3	0.0	--	--	--	--
DD-6 (70/140)	75.7	24.3	0.0	--	--	--	--
DD-7 (70/140)	74.0	24.6	1.4	--	--	--	--
DD-8 (40/70)	71.9	28.1	0.0	--	--	--	--
DD-9 (70/140)	68.4	31.6	0.0	--	--	--	--
DD-10 (40/70)	79.0	18.3	1.5	--	1.5	1.2	
DD-10 (70/140)	75.5	20.2	1.0	--	1.0	2.0	1.3
DD-11 (40/70)	82.0	17.1	0.9	--	0.9	--	
DD-11 (70/140)	76.7	20.9	1.0	--	1.0	--	1.5
DD-12 (40/70)	81.9	16.1	2.0	--	2.0	--	
DD-12 (70/140)	72.2	23.6	1.5	--	1.5	--	2.7
DD-13 (40/70)	81.1	17.5	1.4	--	1.4	--	
DD-13 (70/140)	75.0	20.4	2.8	--	2.8	--	1.8
DD-14 (40/70)	78.2	19.9	1.1	--	1.1	--	0.8
DD-15 (40/70)	81.9	16.9	1.2	--	1.2	--	--
DD-16 (70/140)	73.3	24.6	0.7	--	--	1.4	--
DD-17 (40/70)	72.8	24.8	1.3	--	--	1.2	--
DD-18 (40/70)	74.0	24.9	1.2	--	--		--
DD-19 (70/140)	69.7	27.9	1.8	--	--	0.6	--
DD-20 (70/140)	72.3	25.0	1.5	--	--	1.2	--
DD-21 (50/140)	71.4	26.5	1.4	--	--	0.7	--
DD-22 (70/140)	71.1	26.5	1.3	--	--	1.1	--

[3] *Washed Sample Analysis on Selected Size Class in Weight % with Rietveld Refinement.*

[4] *Undifferentiated.*

-- Mineral not detected.

Mineral Name	Chemical Composition
Quartz	SiO_2
Albite	$NaAlSi_3O_8$
Microcline	$KAlSi_3O_8$
Illite	Variable-Mica Like Clay Minerals
Clinochlore	$Mg_5Al(AlSi_3O_{10})(OH)_8$
Indialite	$Mg_2Al_3(AlSi_5O_{18})$
Magnetite	Fe_3O_4

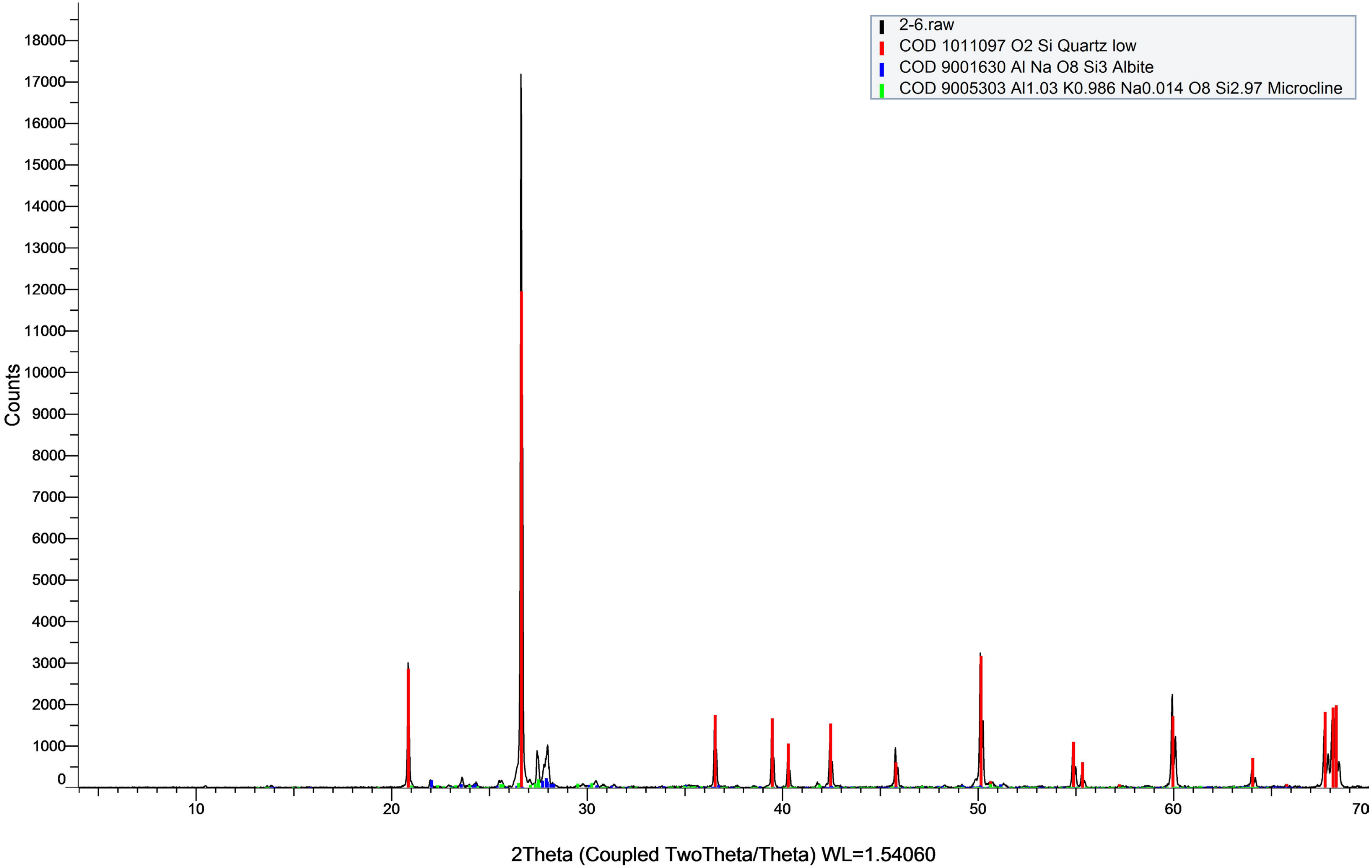


Figure A-II-1. XRD phase diagram for windblown sand sample DD-1 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

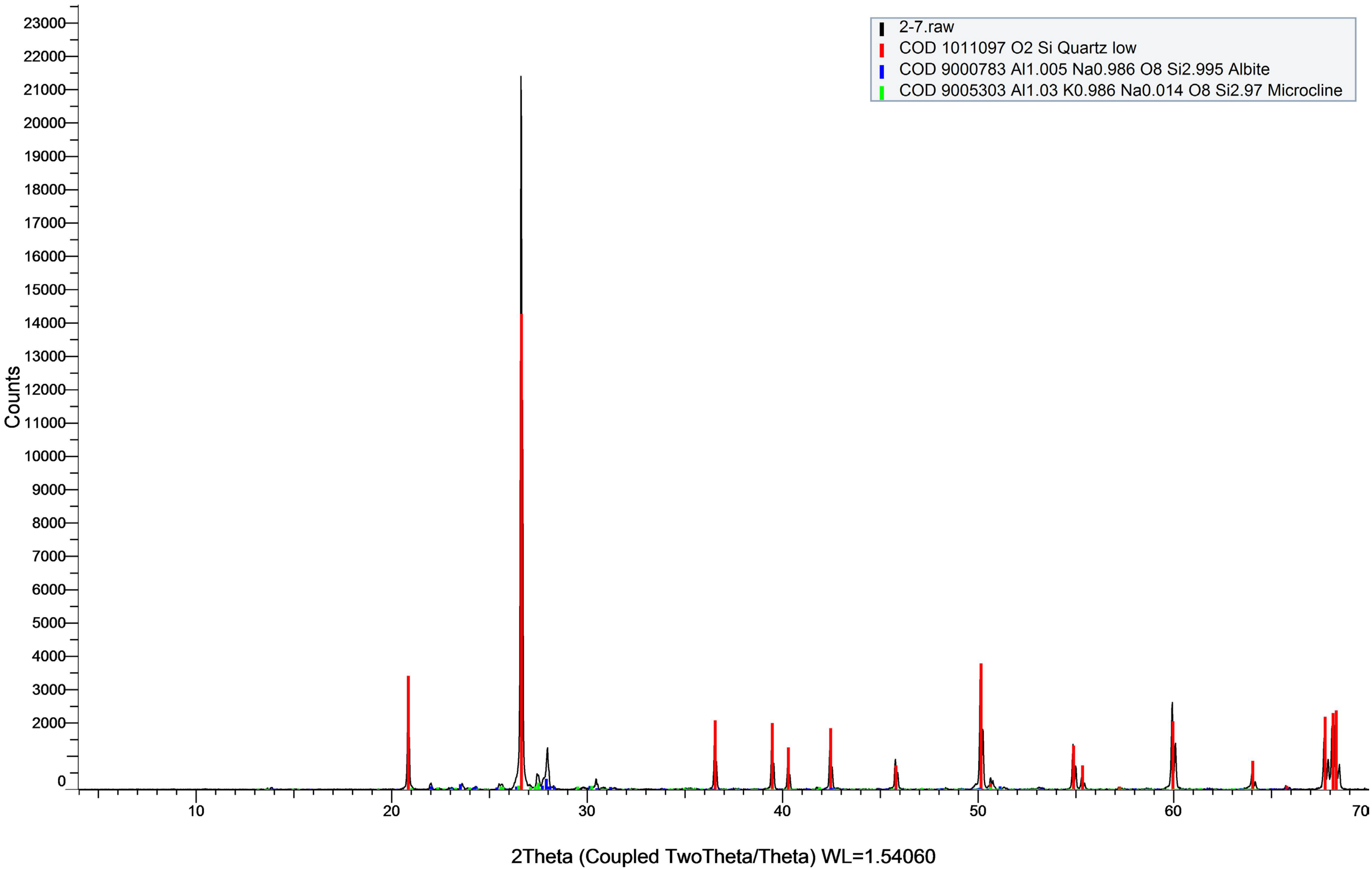


Figure A-II-2. XRD phase diagram for windblown sand sample DD-2 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

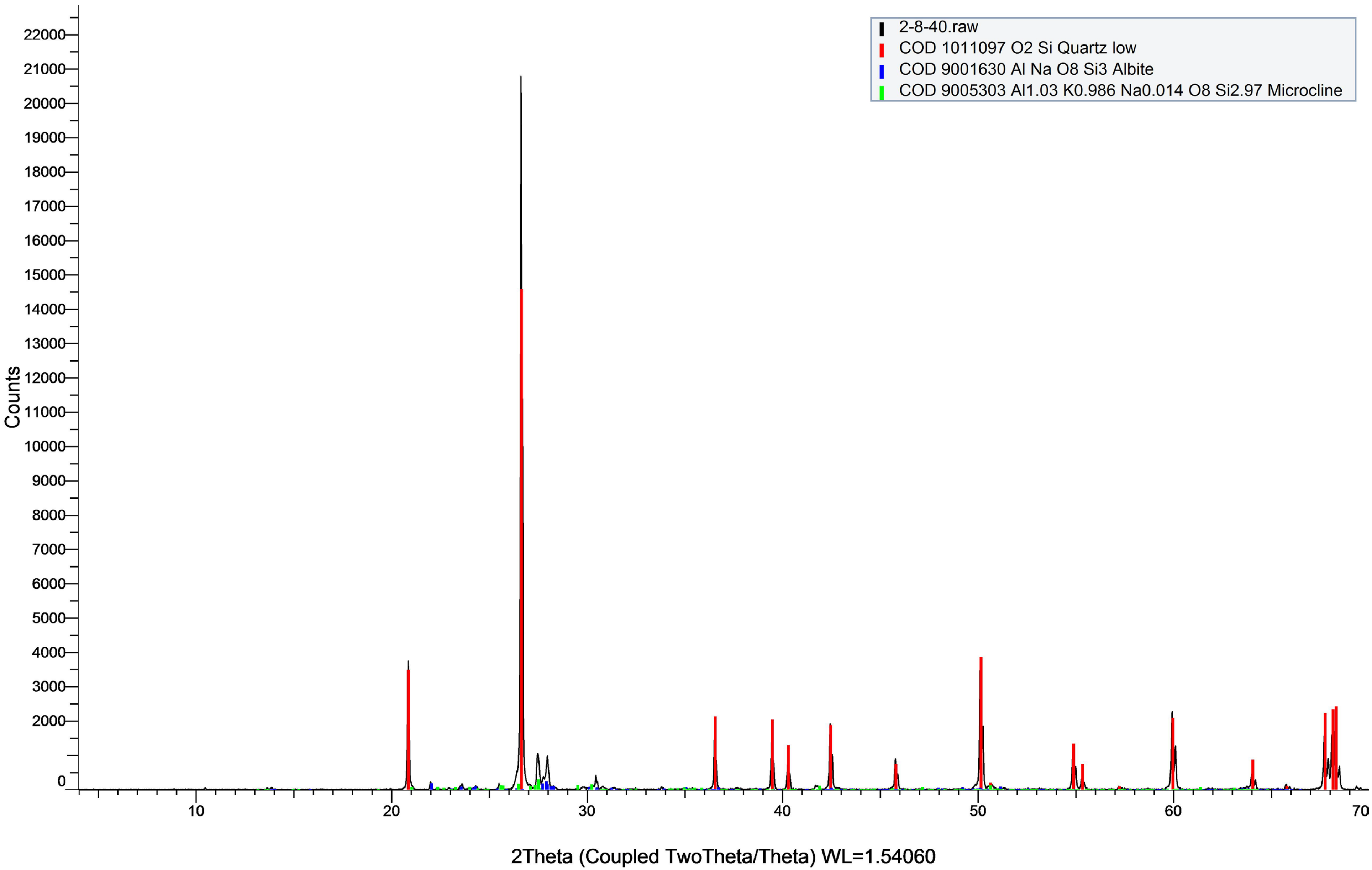


Figure A-II-3. XRD phase diagram for windblown sand sample DD-3a 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

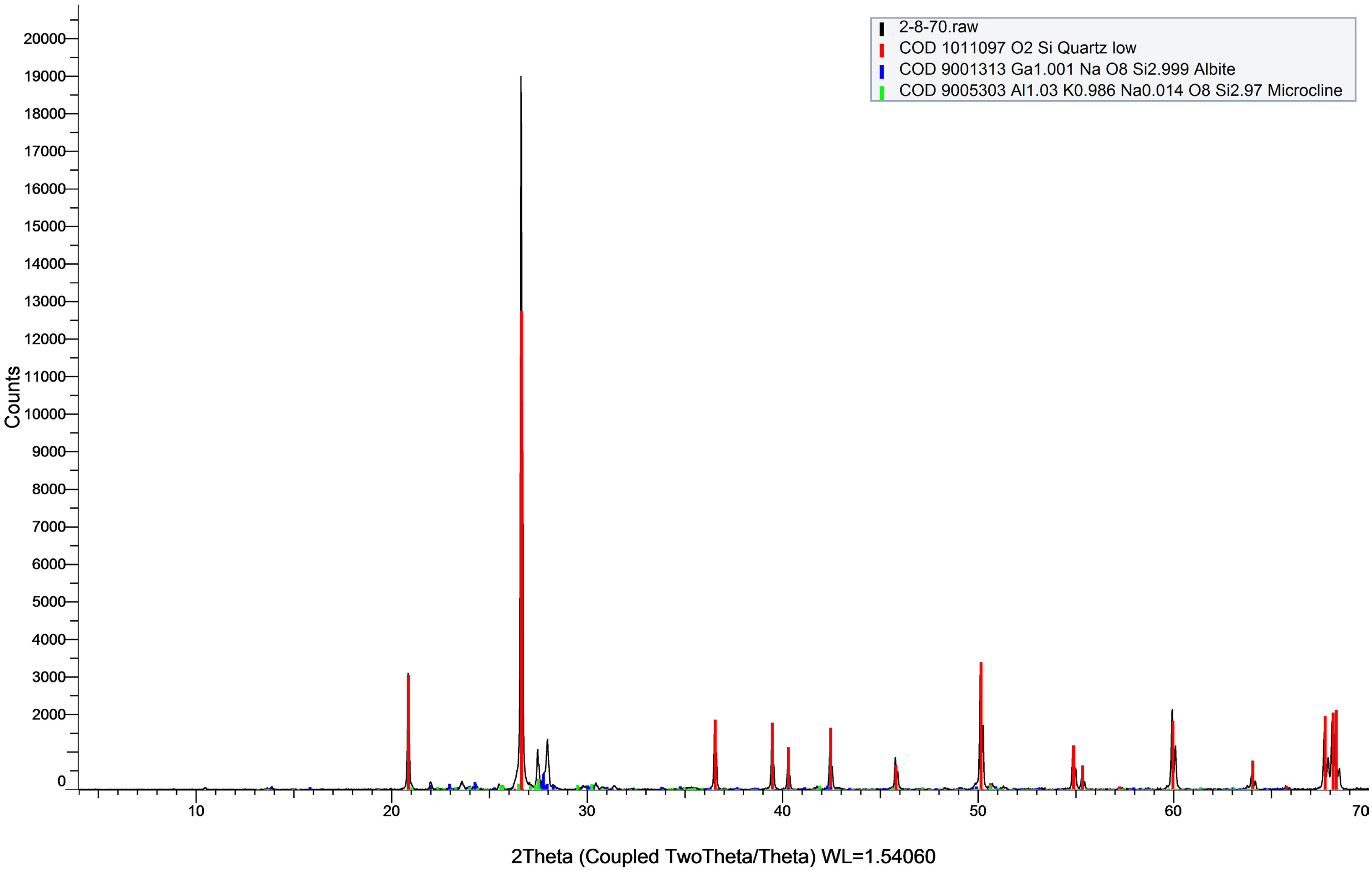


Figure A-II-4. XRD phase diagram for windblown sand sample DD-3b 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

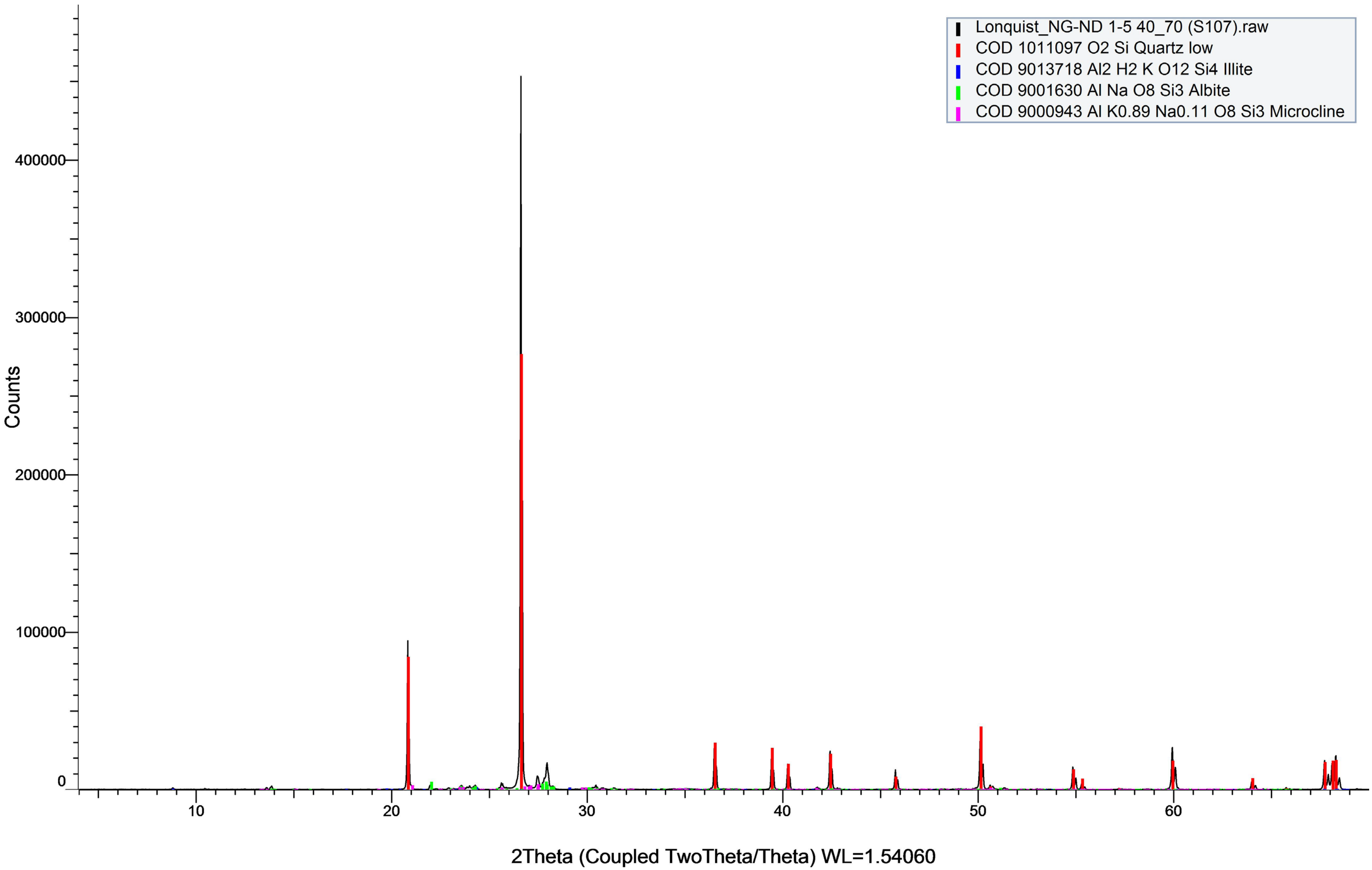


Figure A-II-5. XRD phase diagram for windblown sand sample DD-4a 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

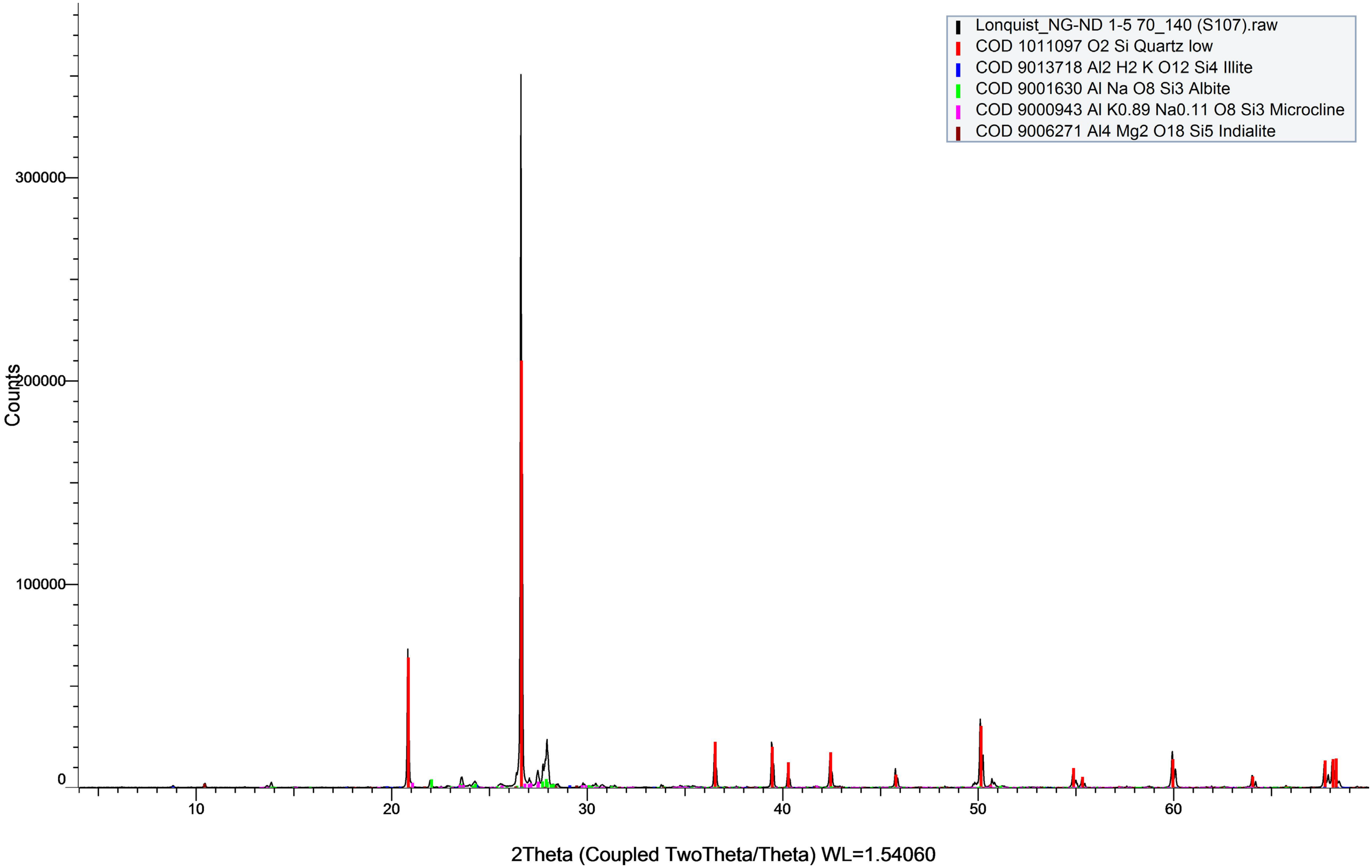


Figure A-II-6. XRD phase diagram for windblown sand sample DD-4b 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

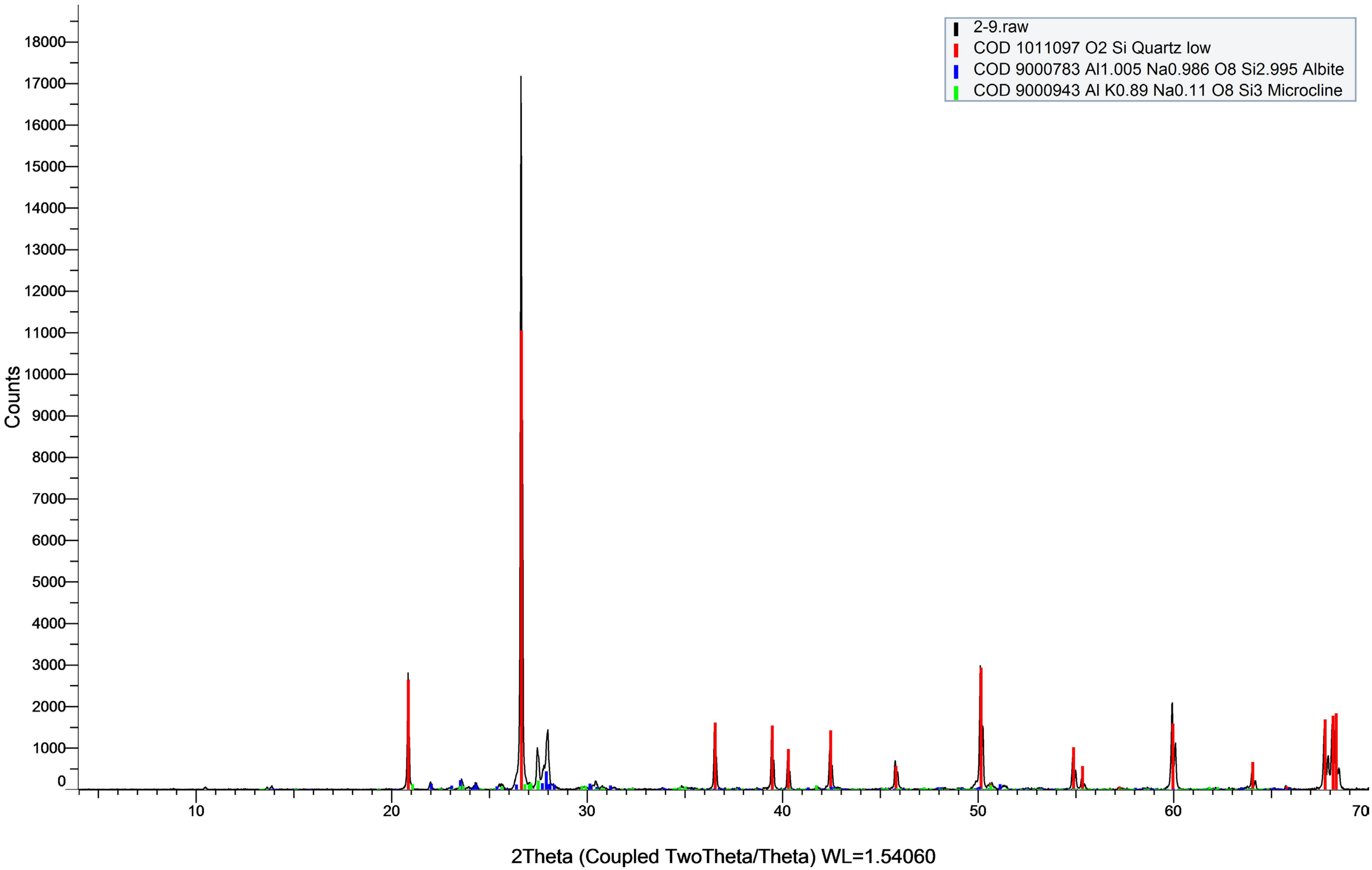


Figure A-II-7. XRD phase diagram for windblown sand sample DD-5 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

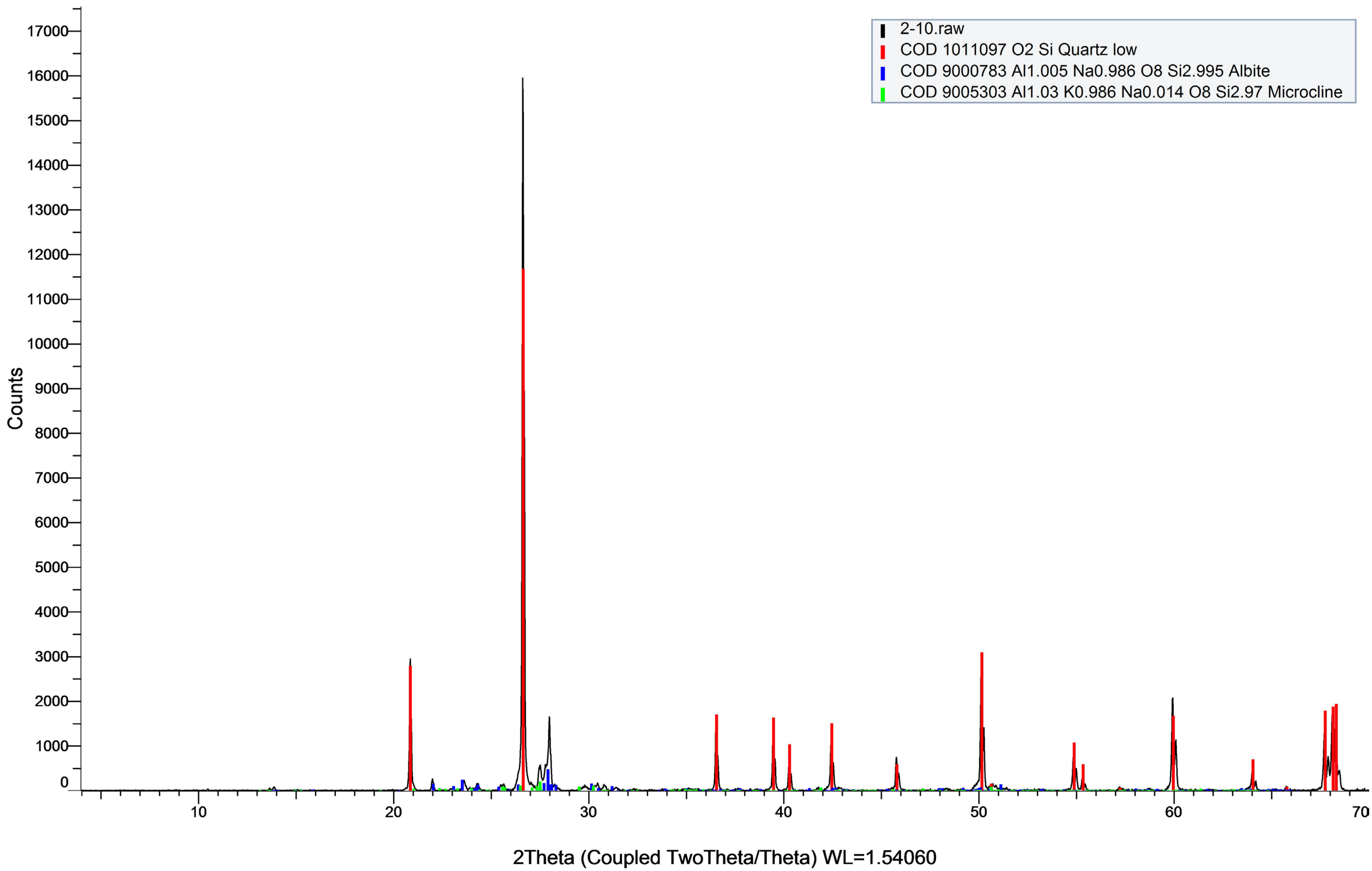


Figure A-II-8. XRD phase diagram for windblown sand sample DD-6 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

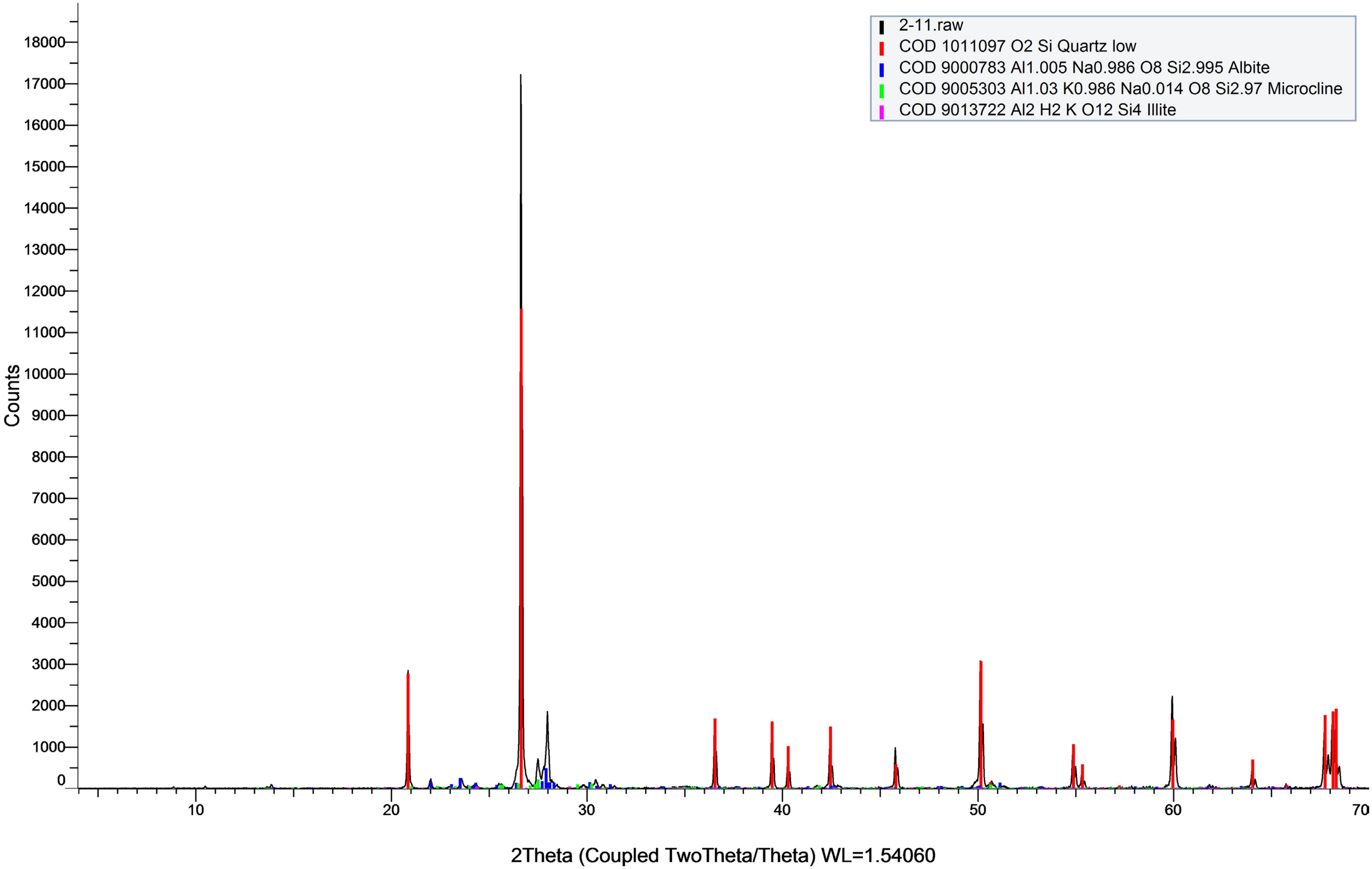


Figure A-II-9. XRD phase diagram for windblown sand sample DD-7 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

NS2-13 70-140 ● Autosampler-Dtex — WPF Report

Scan ID: NS2-13_70-140.raw ● NS2-13 70-140 ● Autosampler-Dtex

Scan Parameters: 5.0°/75.0°/0.02°/0.24(s), I(p)=126342/948, Cu(40kV,40mA), Wednesday, October 23, 2019, 10:47 AM

☑ Zero Offset = 0.0052 (0.0005)	☐ Displacement = 0.0	☐ Distance Slack = 0.0
☑ Kα2 Peaks Present	☐ Kα2/Kα1 Ratio = 0.5	☐ X-Ray Polarization = 1.0

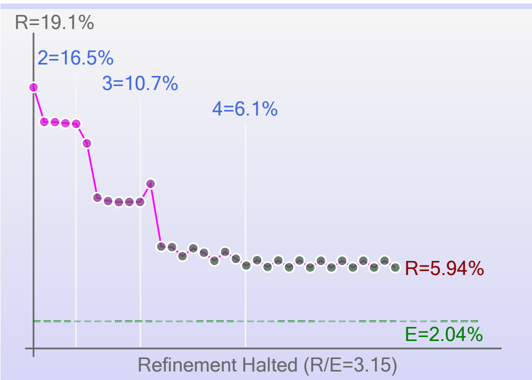
Geometry: Diffractometer Lp   Fitted-Range: 5.0° - 75.0°   BG-Model: Polynomial (5)   λ: 1.54059 Å (Cu)

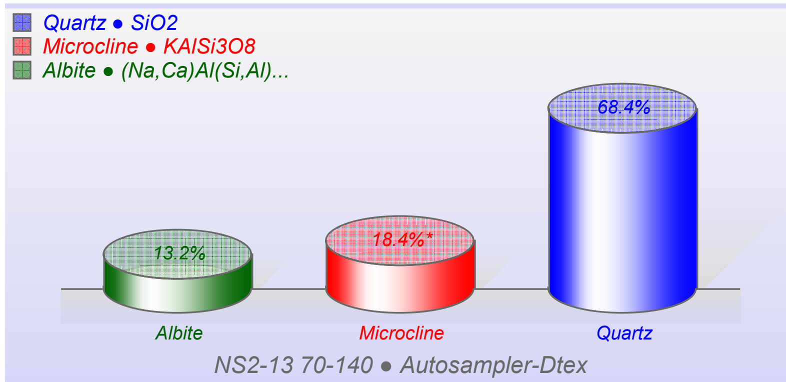
PSF: pseudo-Voigt   Broadening: Individual FWHM Curve   Instrument: Constant FWHM = 0.1°

Phase ID (3)	Chemical Formula	PDF-#	Wt% (ESD)	RIR	μ
Quartz	SiO_2	98-000-7648	68.4 (0.7)	4.11	91.2
Microcline	$KAlSi_3O_8$	00-019-0932	18.4 (0.6)	(1.0)	62.3
Albite (?)	$(Na,Ca)Al(Si,Al)_3O_8$	00-041-1480	13.2 (0.4)	1.06	54.3

XRF(Wt%): Ca=1.0%, K=2.6%, Si=39.6%, Al=5.1%, Na=0.6%, O=51.2%

Refinement Halted (R/E=3.15), ♣ Round=4, Iter=13, P=162, R=6.42% (E=2.04%, EPS=0.5)





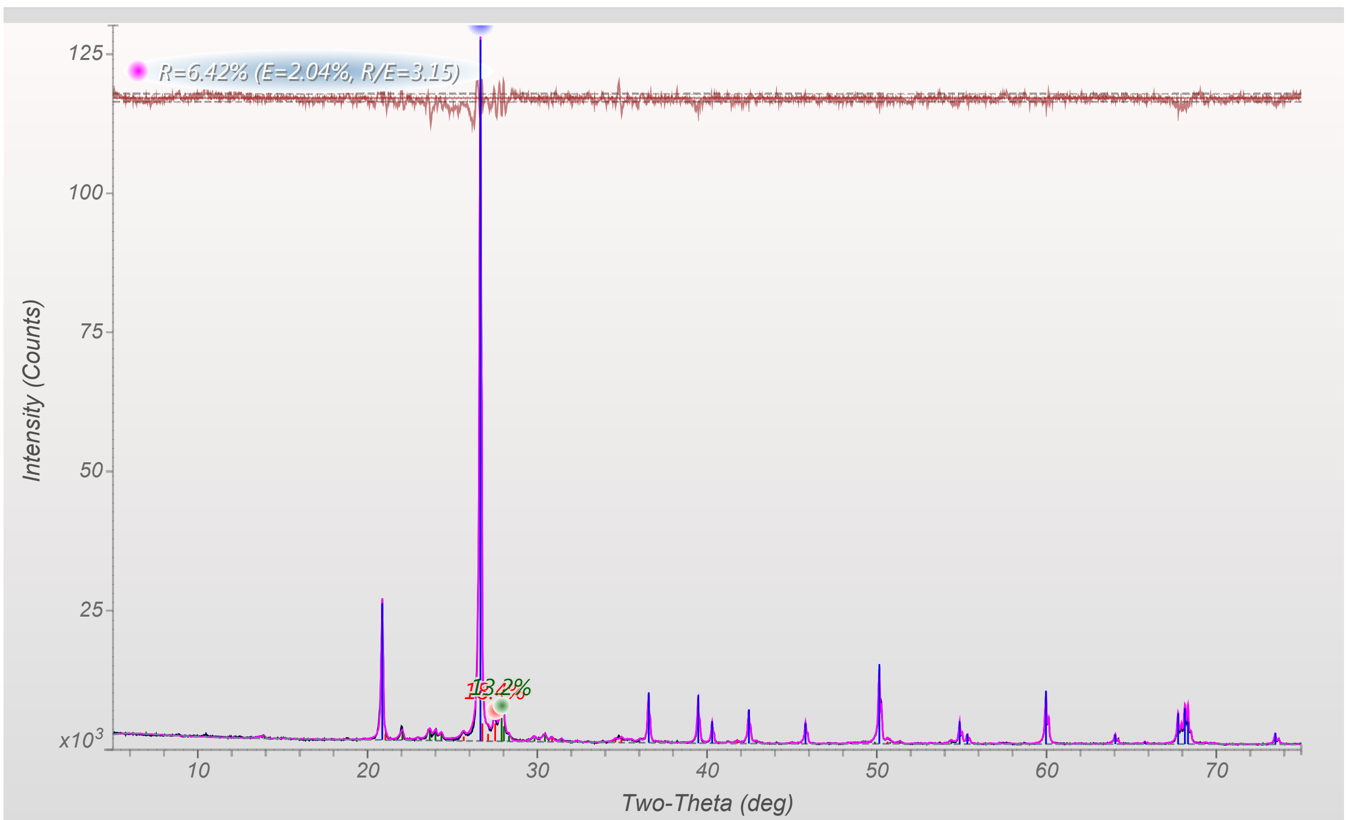


Figure A-II-10. XRD phase diagram for windblown sand sample DD-8 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

NS2-13 70-140 ● Autosampler-Dtex	WPF Report

Scan ID: NS2-13_70-140.raw ● NS2-13 70-140 ● Autosampler-Dtex

Scan Parameters: 5.0°/75.0°/0.02°/0.24(s), I(p)=126342/948, Cu(40kV,40mA), Wednesday, October 23, 2019, 10:47 AM

☑ Zero Offset = 0.0052 (0.0005)	☐ Displacement = 0.0	☐ Distance Slack = 0.0
☑ Kα2 Peaks Present	☐ Kα2/Kα1 Ratio = 0.5	☐ X-Ray Polarization = 1.0

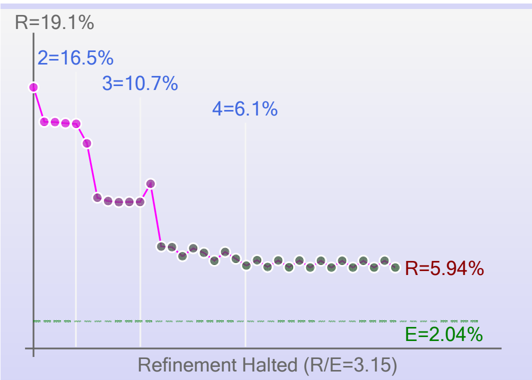
Geometry: Diffractometer Lp   Fitted-Range: 5.0° - 75.0°   BG-Model: Polynomial (5)   λ: 1.54059 Å (Cu)

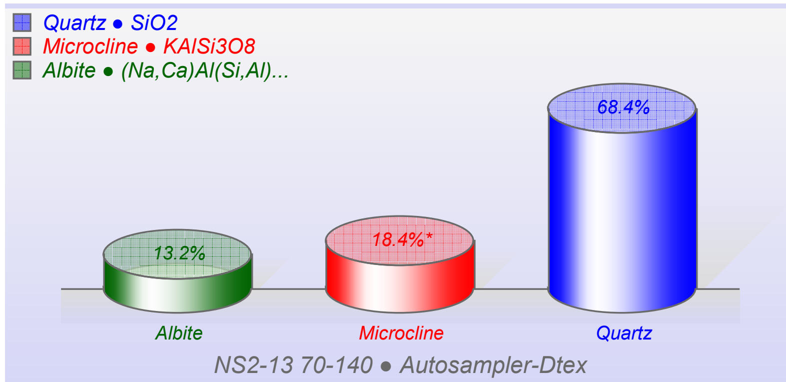
PSF: pseudo-Voigt   Broadening: Individual FWHM Curve   Instrument: Constant FWHM = 0.1°

Phase ID (3)	Chemical Formula	PDF-#	Wt% (ESD)	RIR	μ
Quartz	SiO_2	98-000-7648	68.4 (0.7)	4.11	91.2
Microcline	$KAlSi_3O_8$	00-019-0932	18.4 (0.6)	(1.0)	62.3
Albite (?)	$(Na,Ca)Al(Si,Al)_3O_8$	00-041-1480	13.2 (0.4)	1.06	54.3

XRF(Wt%): Ca=1.0%, K=2.6%, Si=39.6%, Al=5.1%, Na=0.6%, O=51.2%

Refinement Halted (R/E=3.15), ♣ Round=4, Iter=13, P=162, R=6.42% (E=2.04%, EPS=0.5)





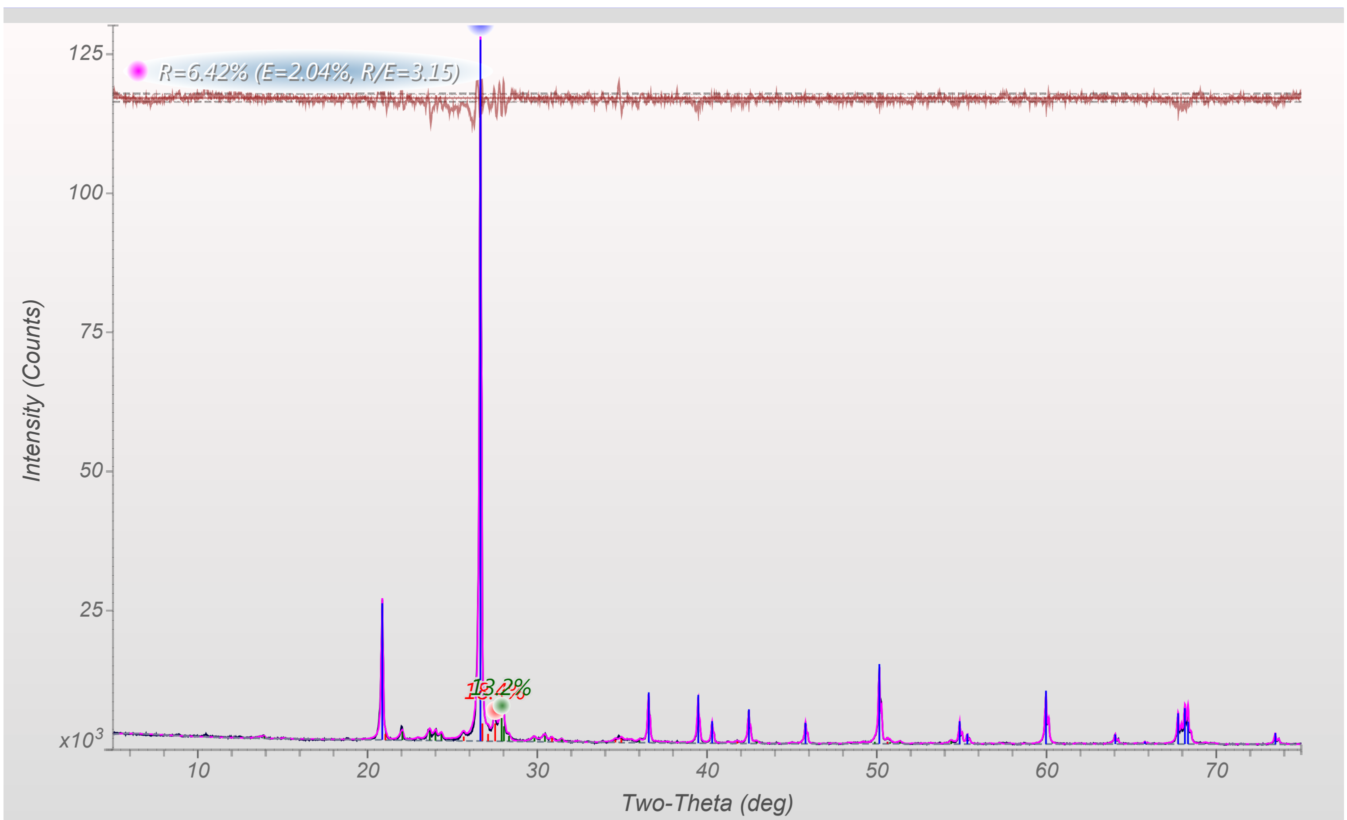


Figure A-II-11. XRD phase diagram for windblown sand sample DD-9 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

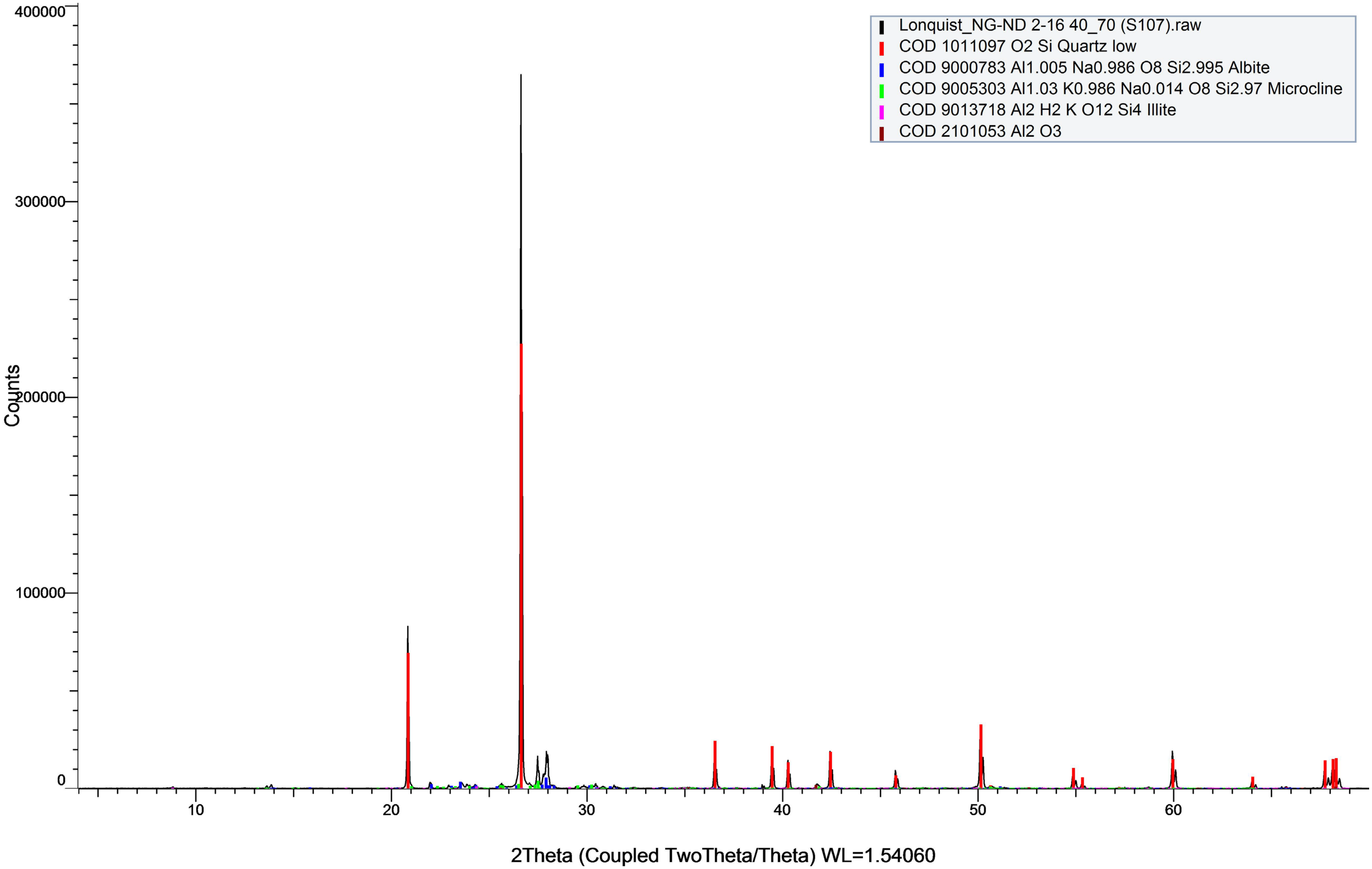


Figure A-II-12. XRD phase diagram for windblown sand sample DD-10a 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

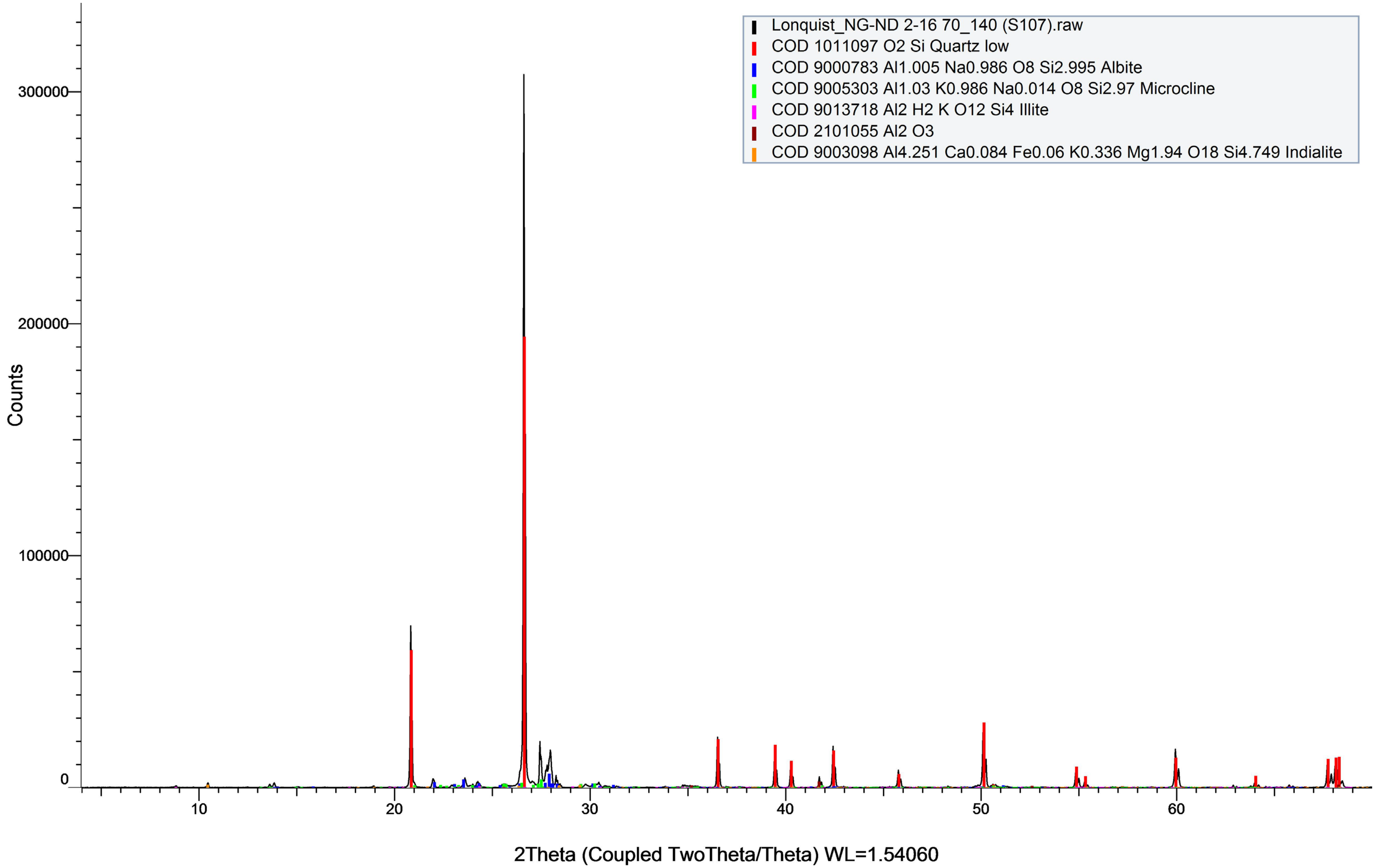


Figure A-II-13. XRD phase diagram for windblown sand sample DD-10b 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

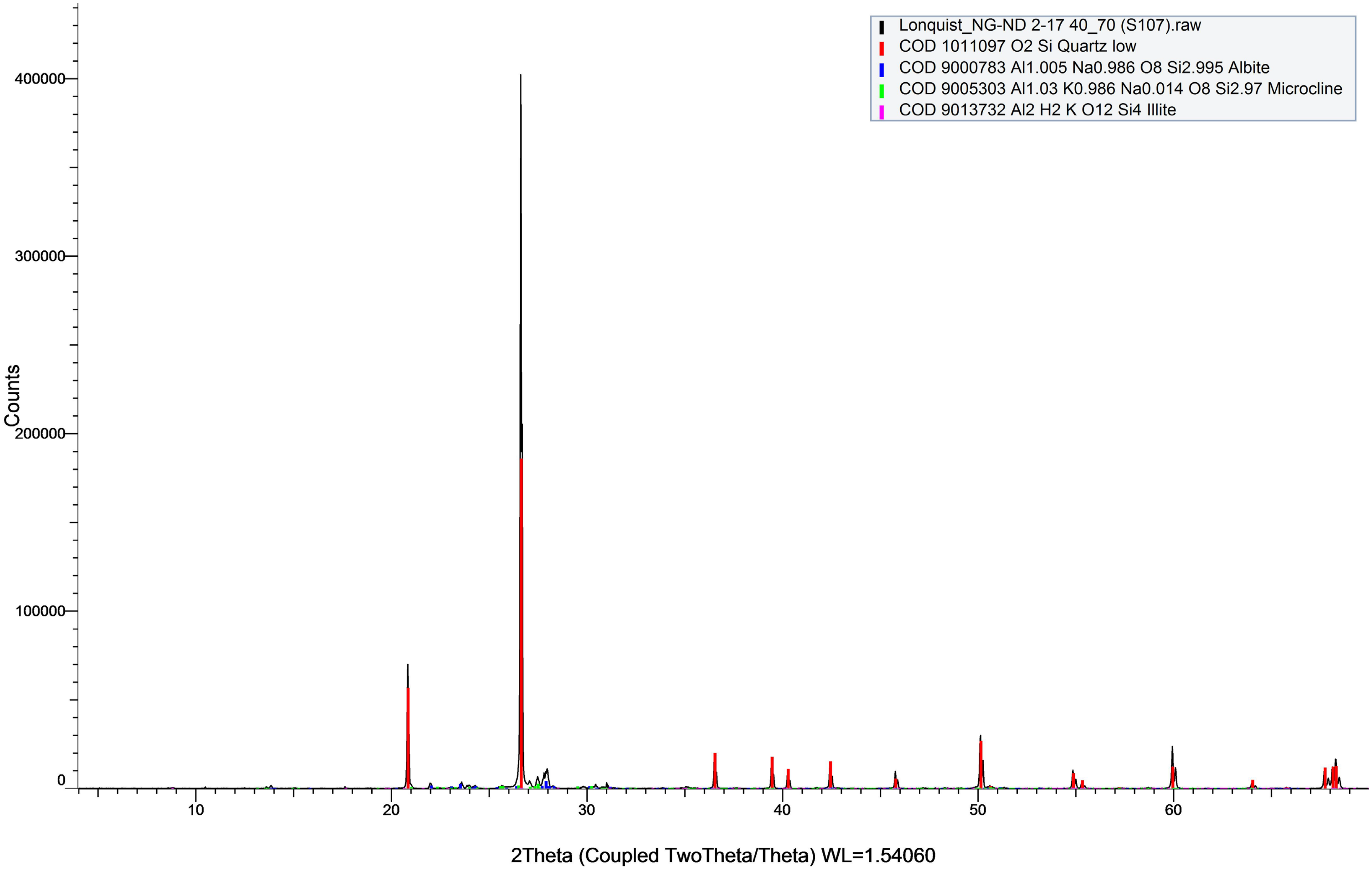


Figure A-II-14. XRD phase diagram for windblown sand sample DD-11a 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

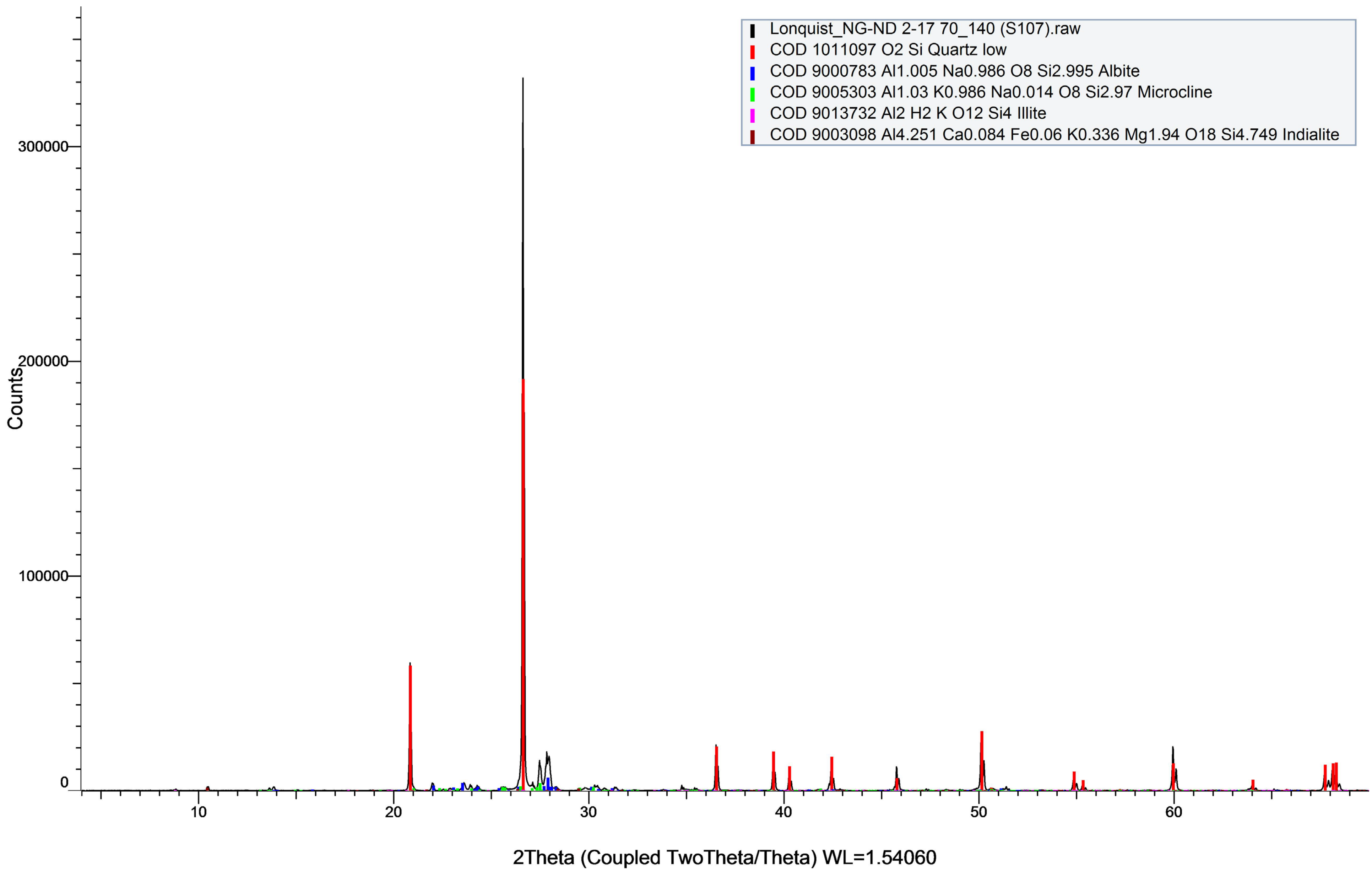


Figure A-II-15. XRD phase diagram for windblown sand sample DD-11b 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

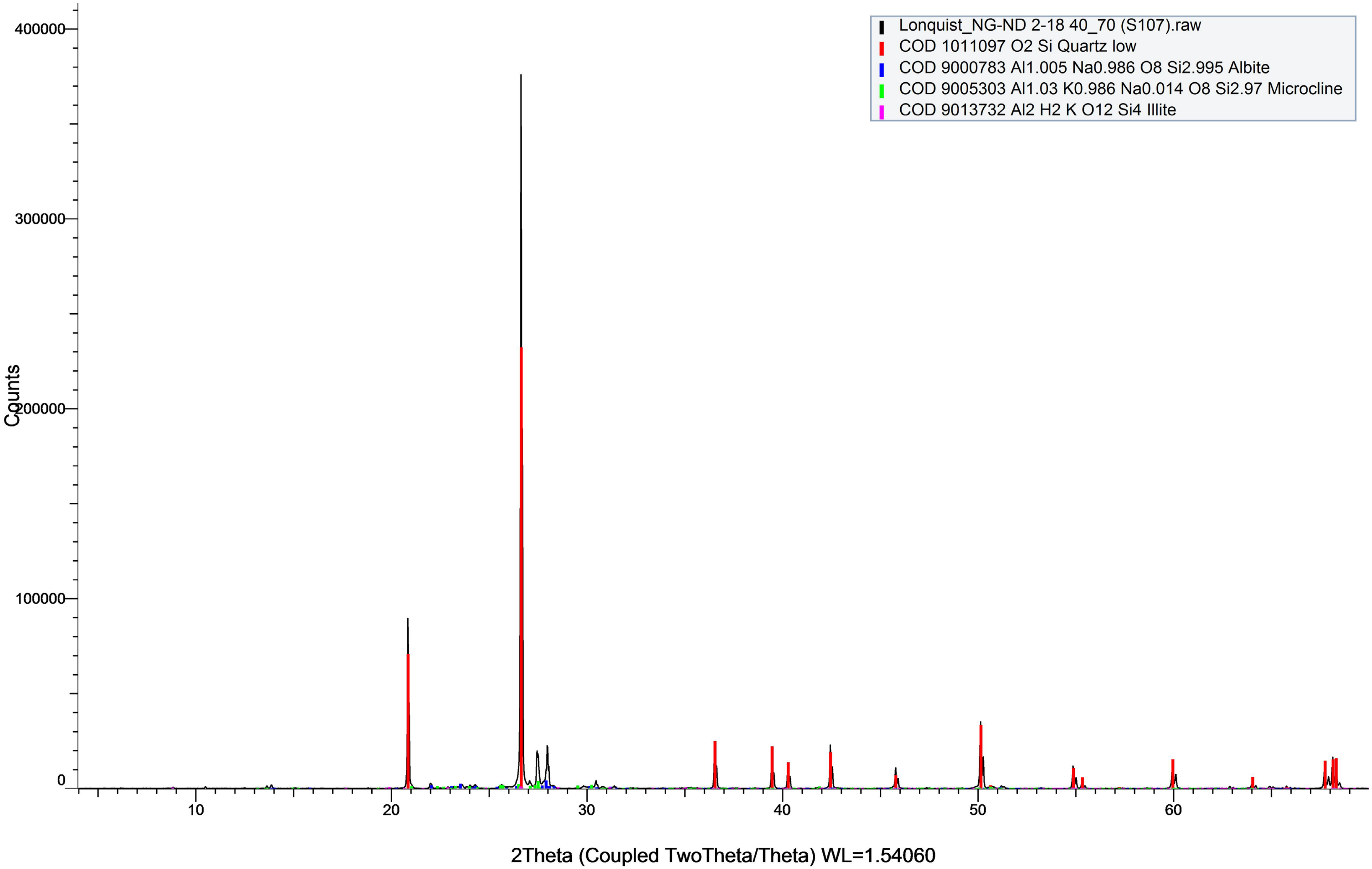


Figure A-II-16. XRD phase diagram for windblown sand sample DD-12a 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

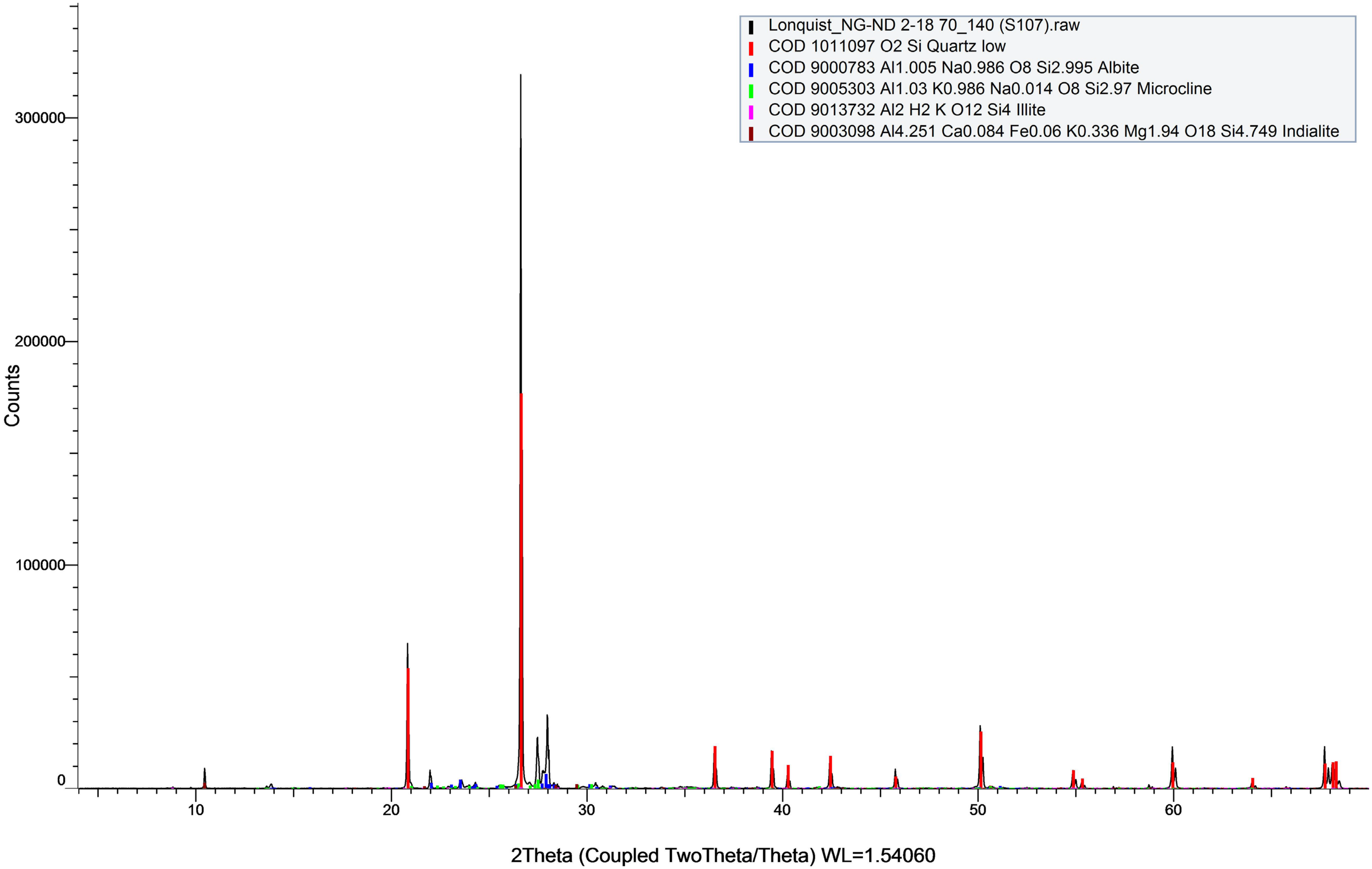


Figure A-II-17. XRD phase diagram for windblown sand sample DD-12b 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

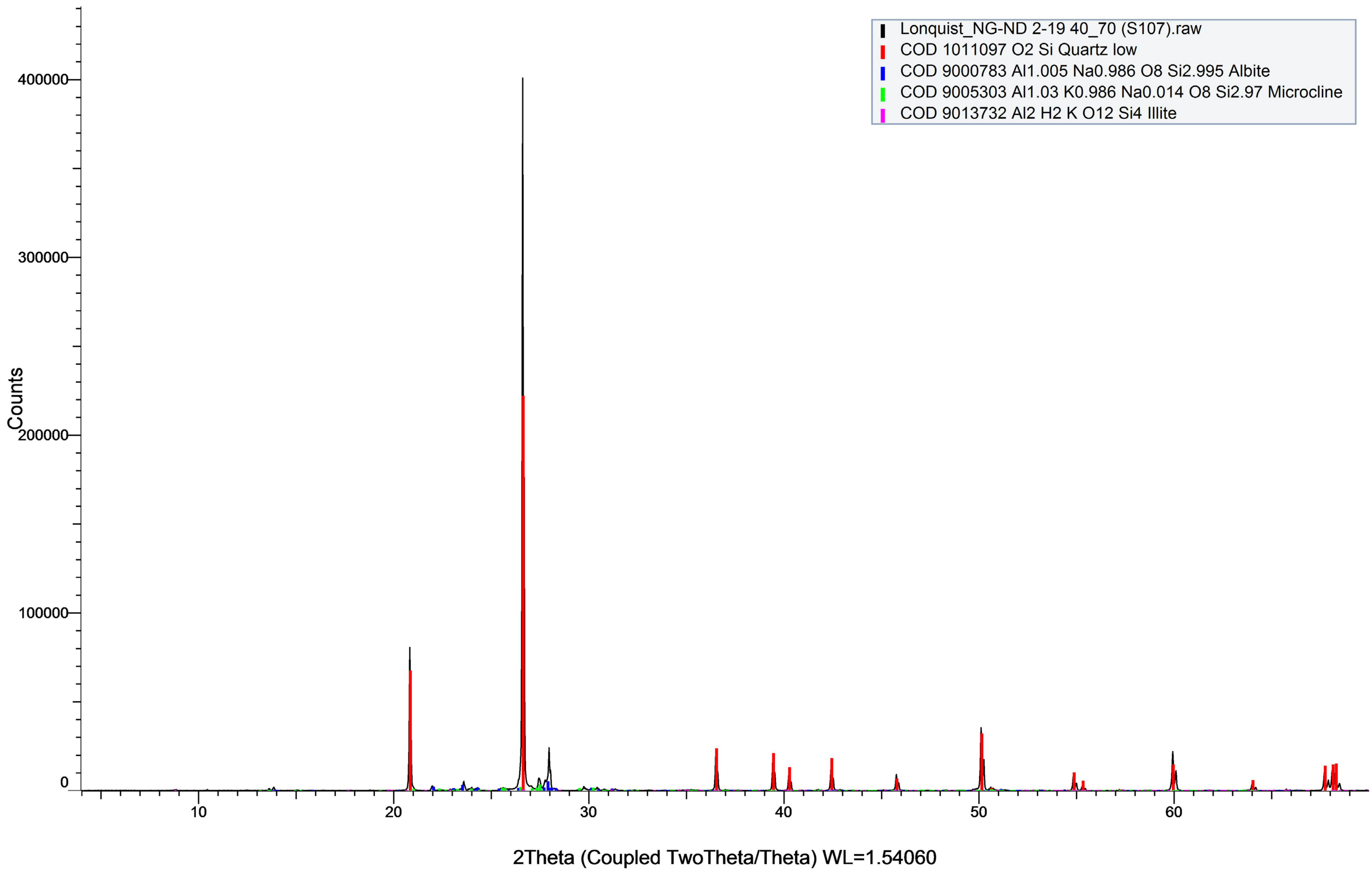


Figure A-II-18. XRD phase diagram for windblown sand sample DD-13a 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

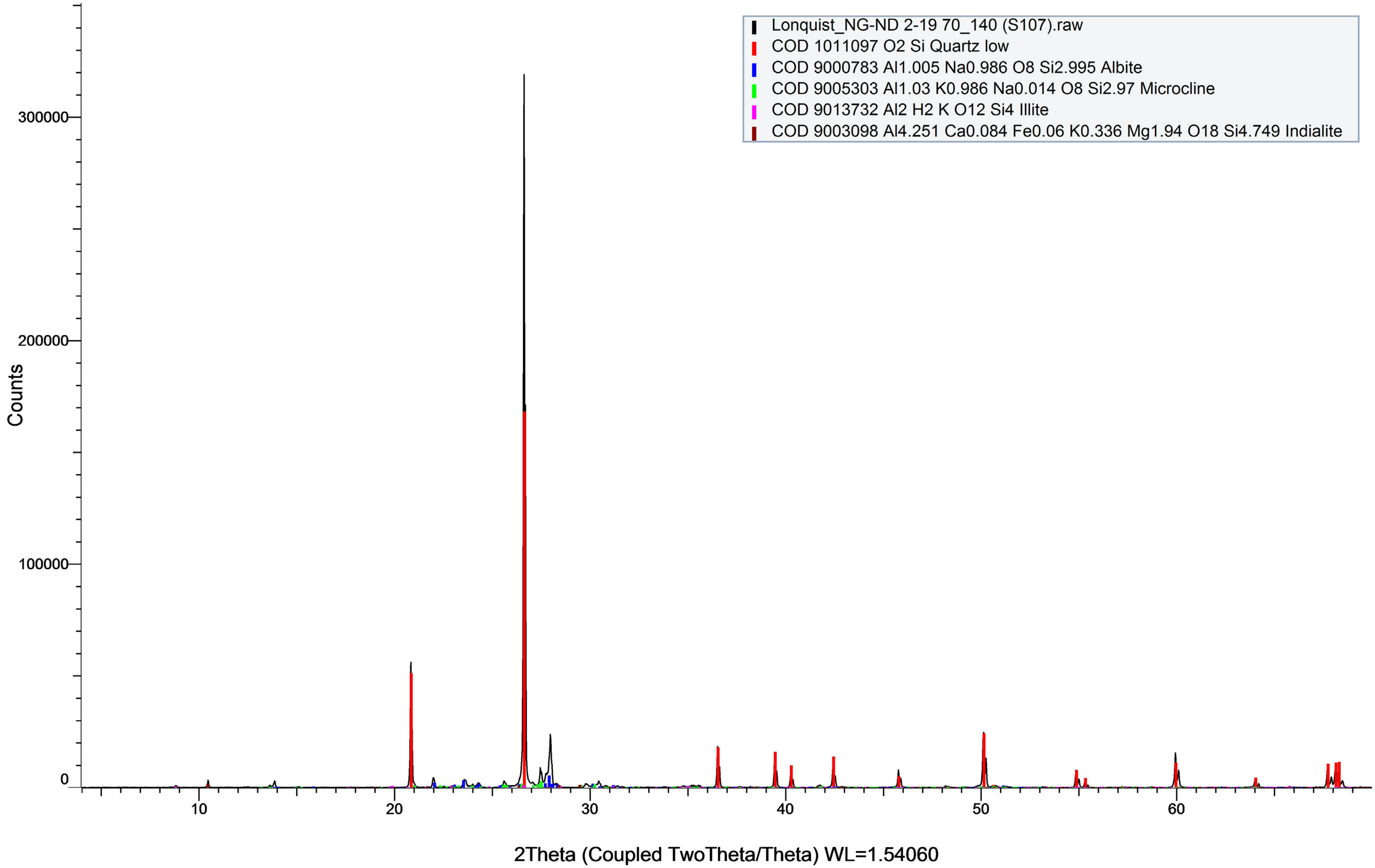


Figure A-II-19. XRD phase diagram for windblown sand sample DD-13b 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

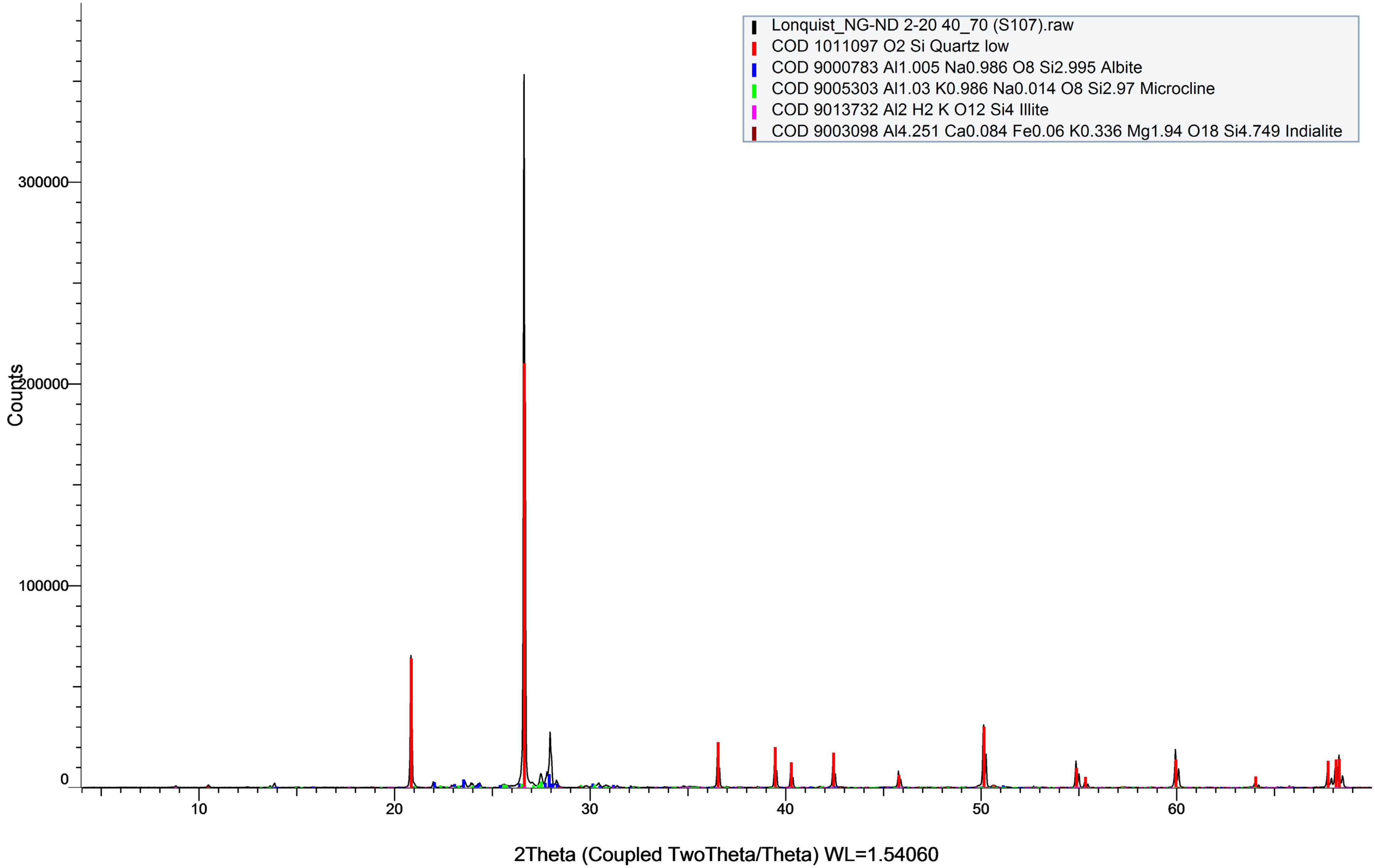


Figure A-II-20. XRD phase diagram for windblown sand sample DD-14 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

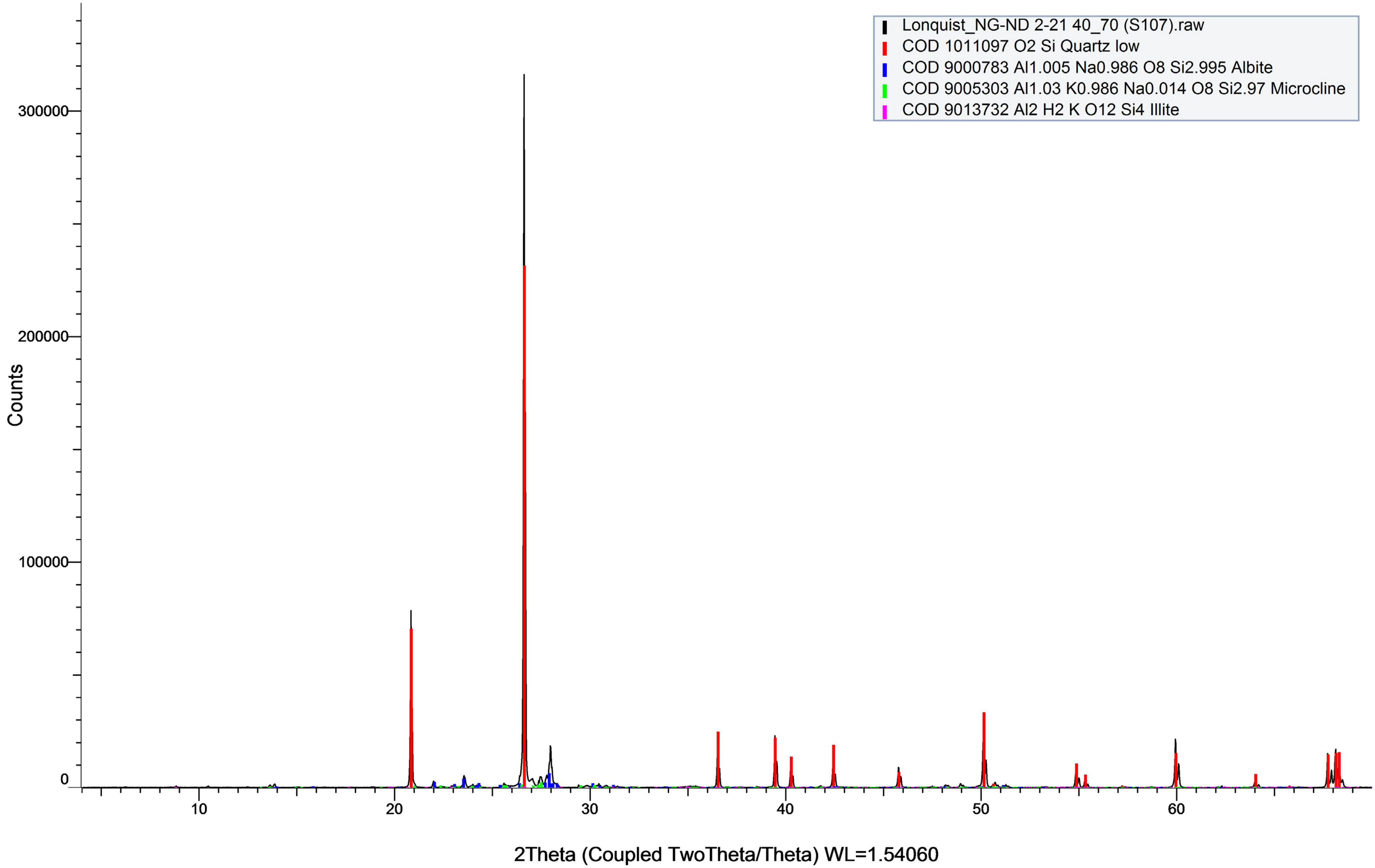


Figure A-II-21. XRD phase diagram for windblown sand sample DD-15 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

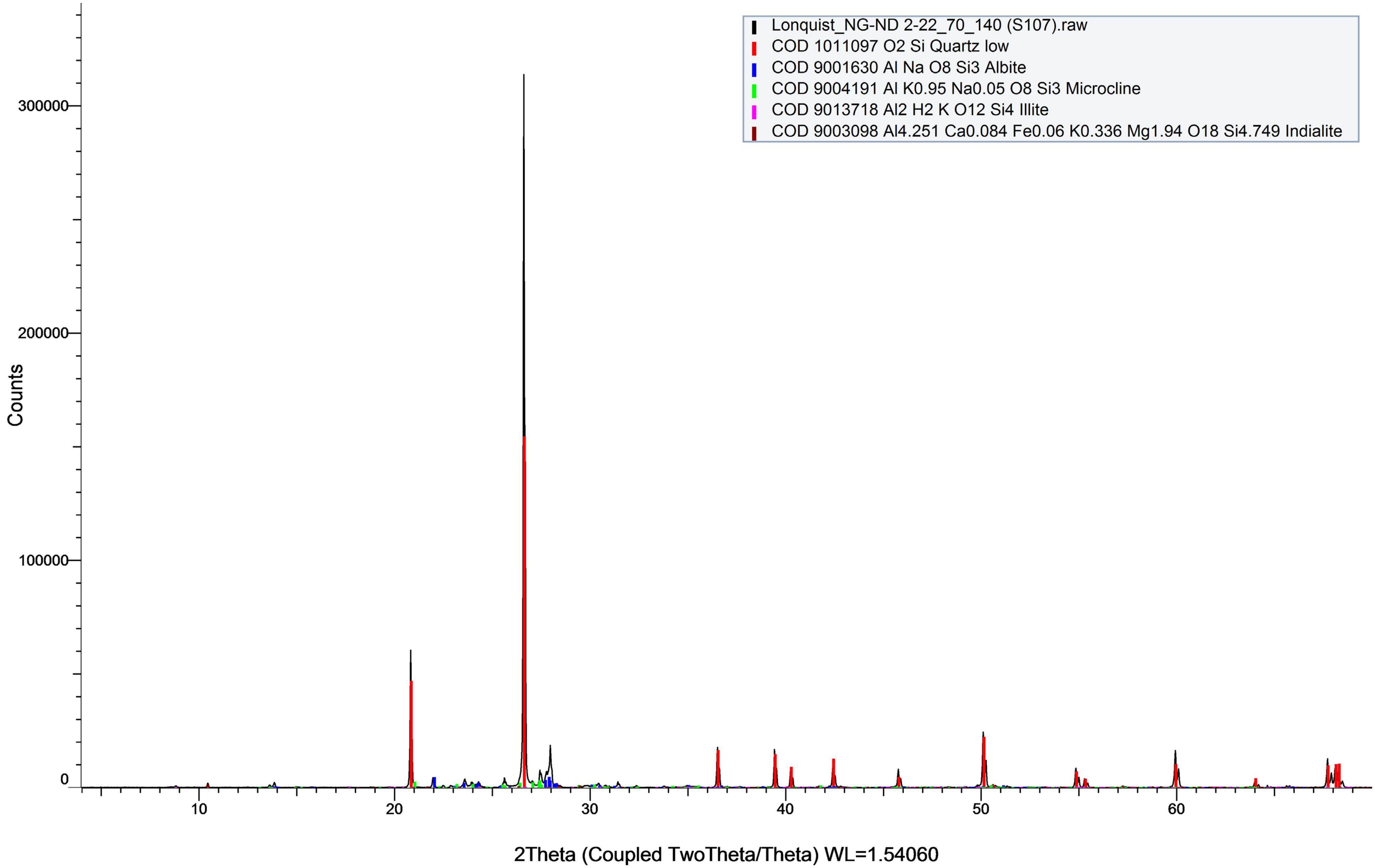


Figure A-II-22. XRD phase diagram for windblown sand sample DD-16 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

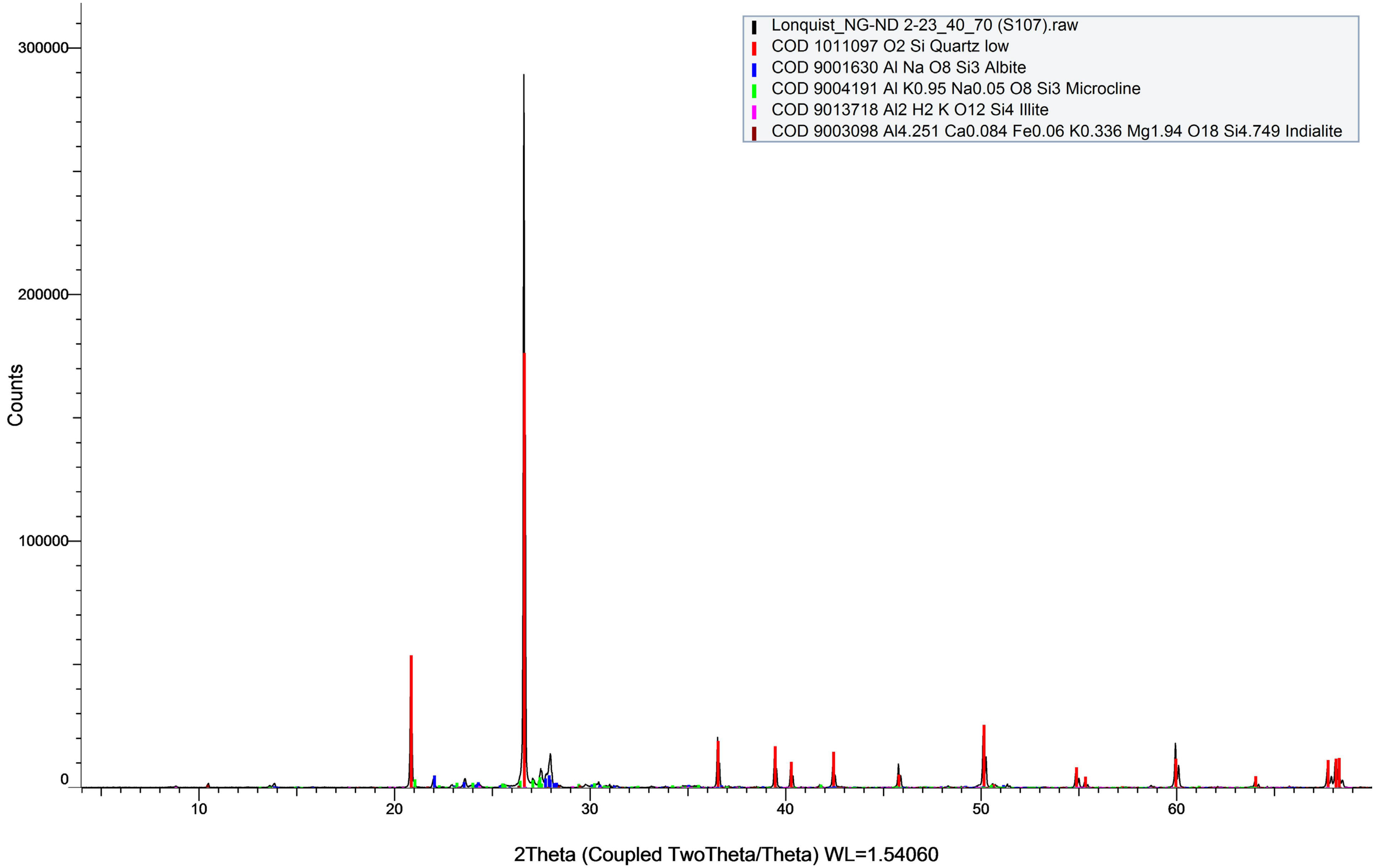


Figure A-II-23. XRD phase diagram for windblown sand sample DD-17 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

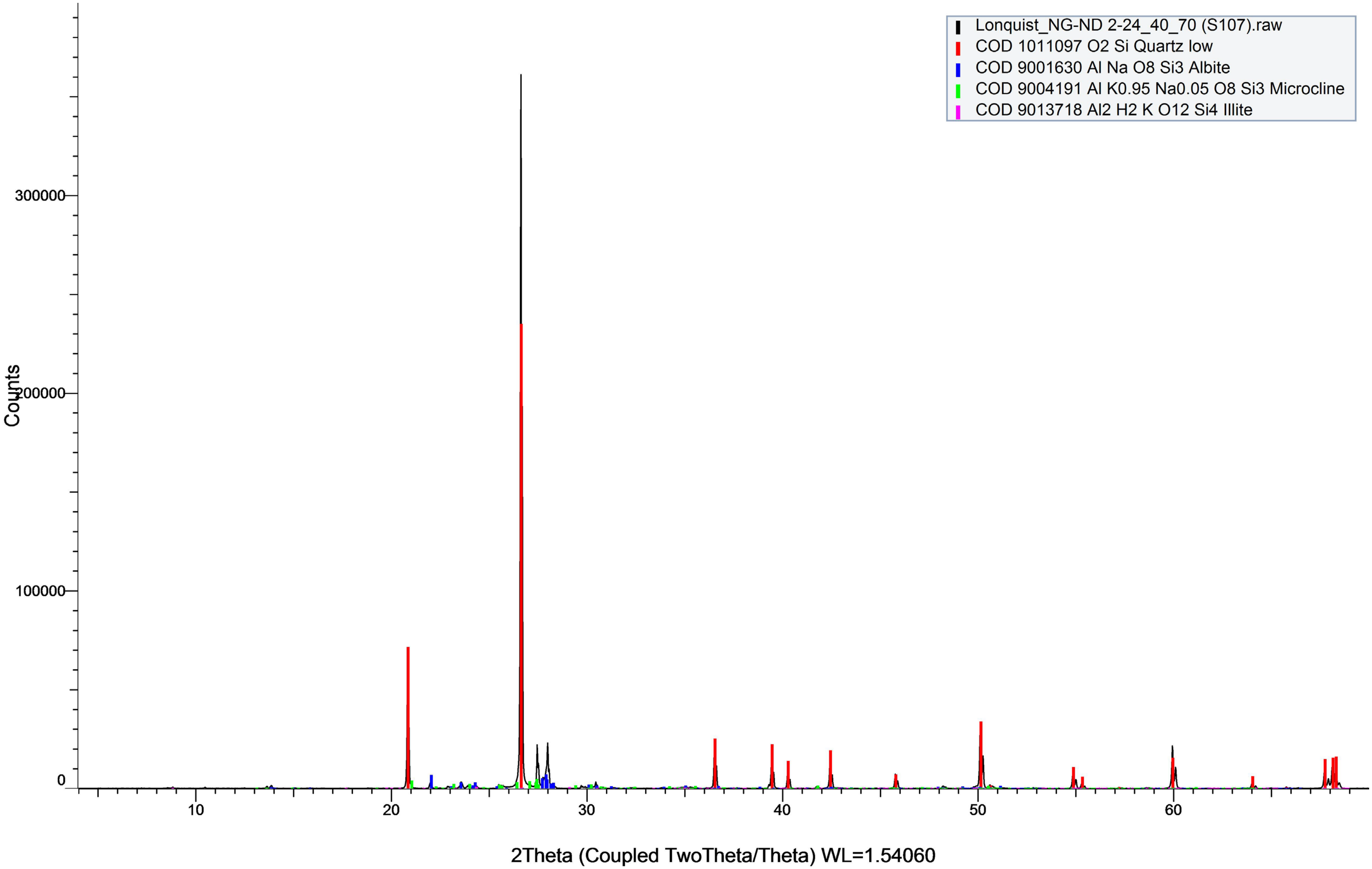


Figure A-II-24. XRD phase diagram for windblown sand sample DD-18 40/70 from the Denbigh Dunes in McHenry County, North Dakota.

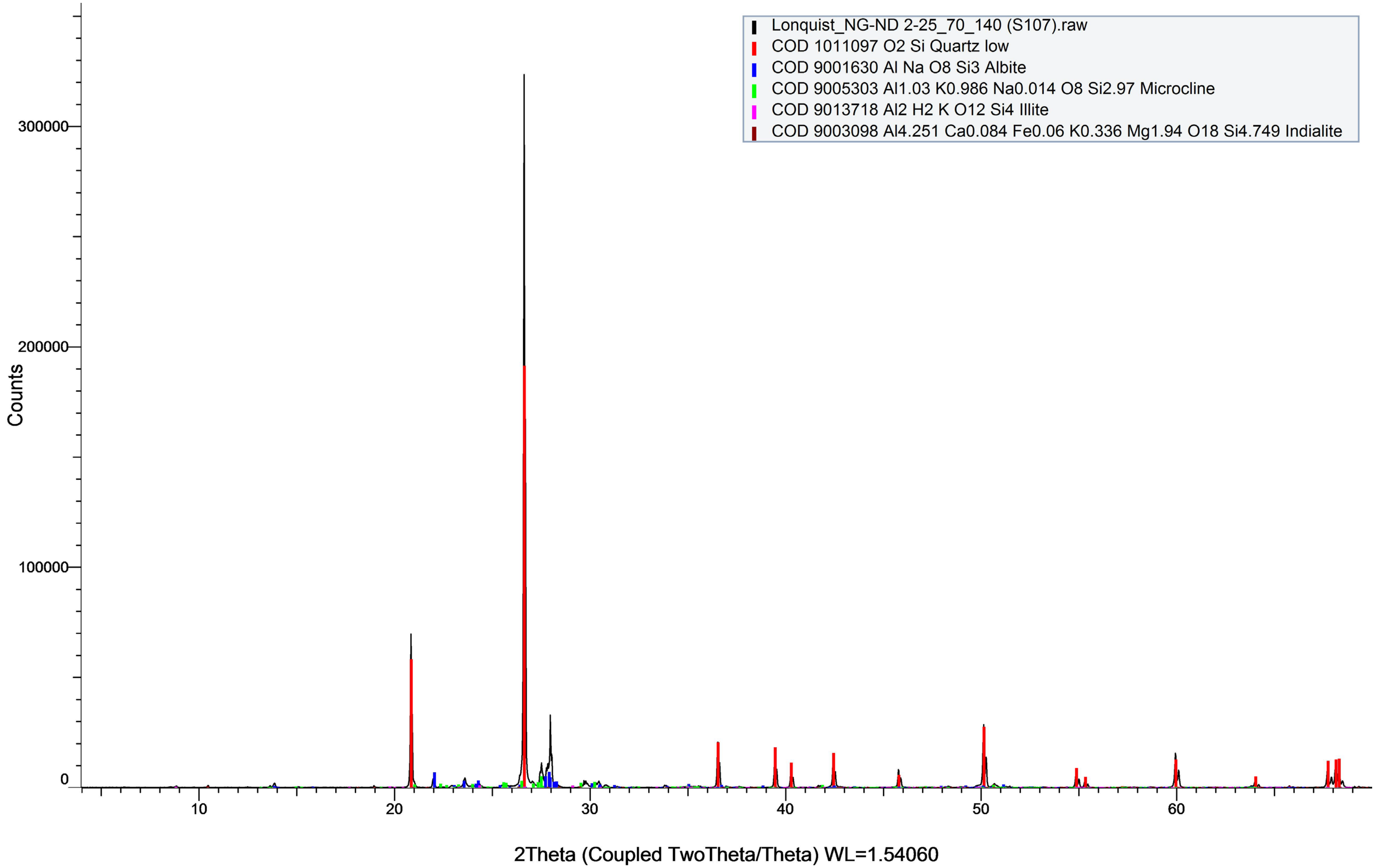


Figure A-II-25. XRD phase diagram for windblown sand sample DD-19 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

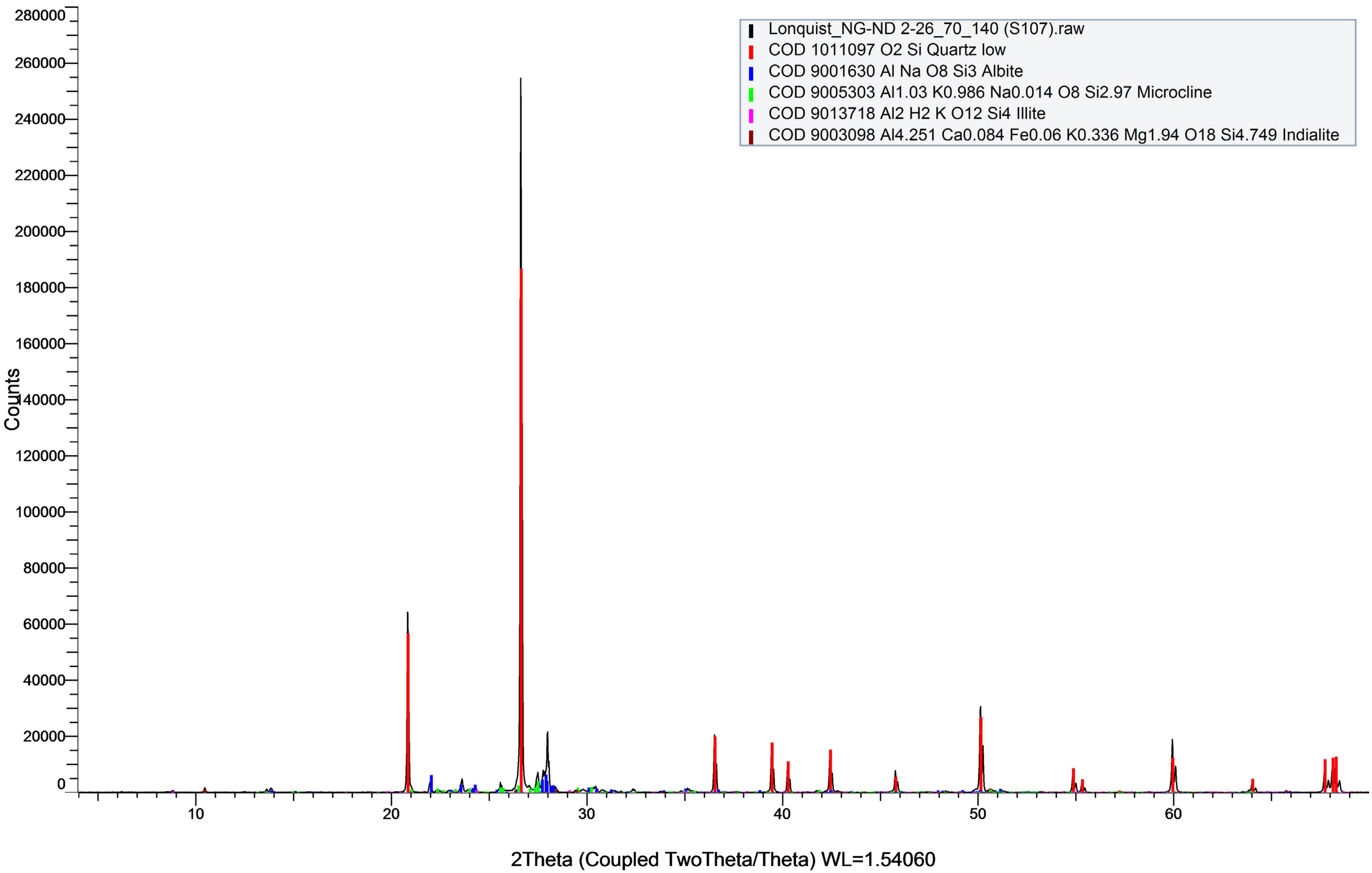


Figure A-II-26. XRD phase diagram for windblown sand sample DD-20 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

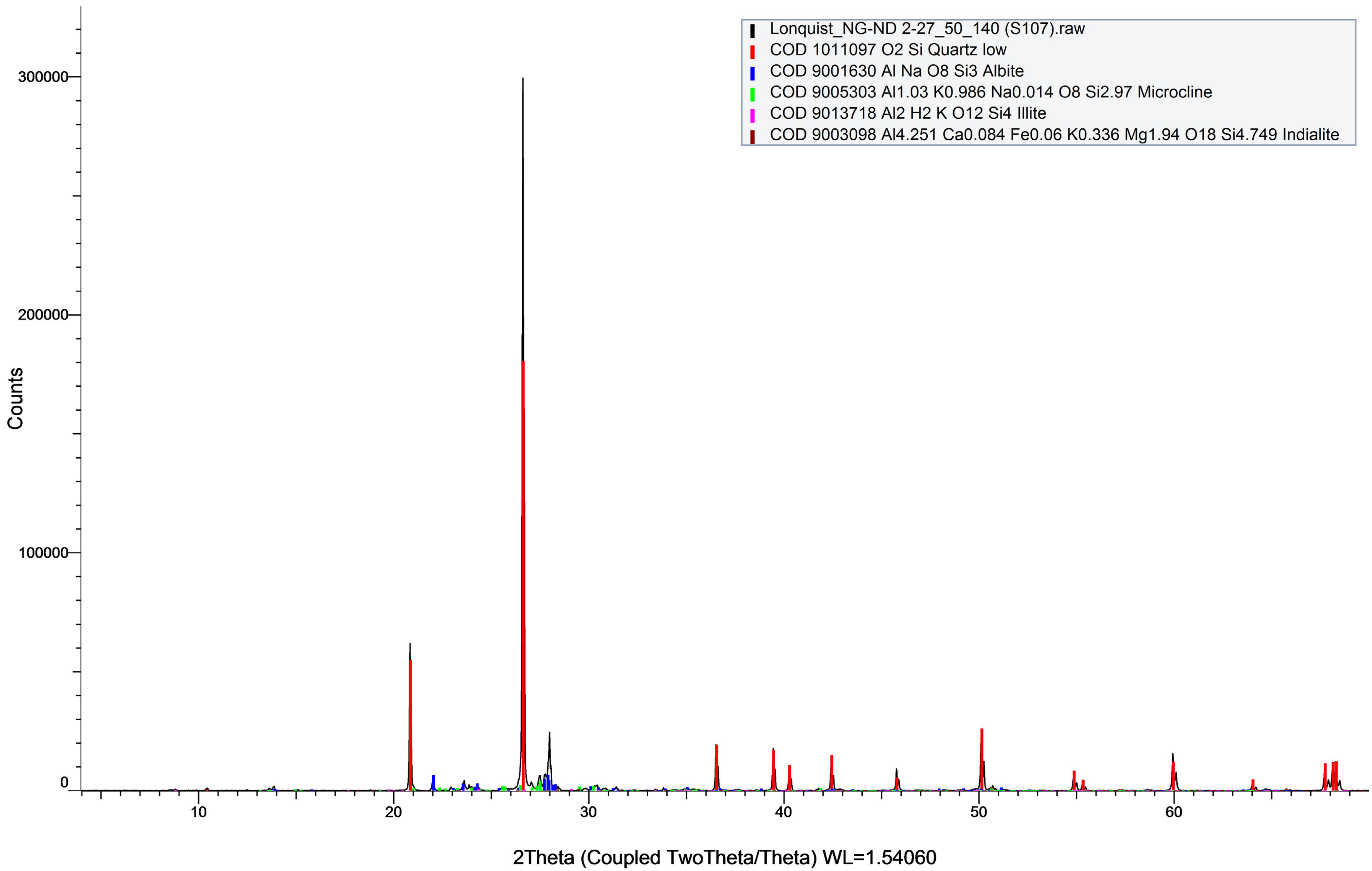


Figure A-II-27. XRD phase diagram for windblown sand sample DD-21 50/140 from the Denbigh Dunes in McHenry County, North Dakota.

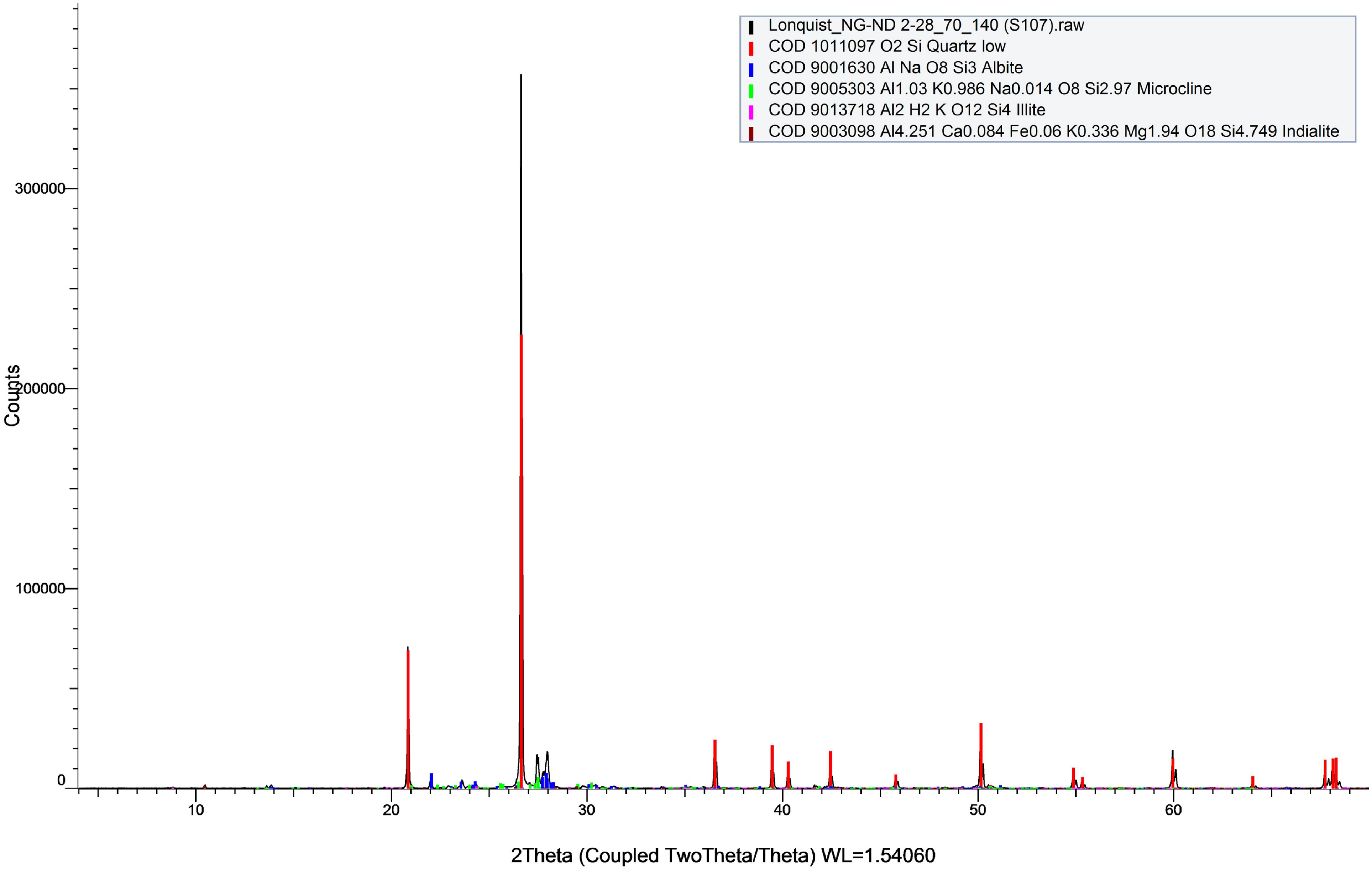


Figure A-II-28. XRD phase diagram for windblown sand sample DD-22 70/140 from the Denbigh Dunes in McHenry County, North Dakota.

APPENDIX III. 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 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 sands sized in the range from 6/12 to 30/50 contain no more than two percent (by weight) HCL-HF soluble constituents, and sands sized in the range from 40/70 to 70/140 contain no more than three percent (by weight) HCL-HF soluble constituents.

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

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

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