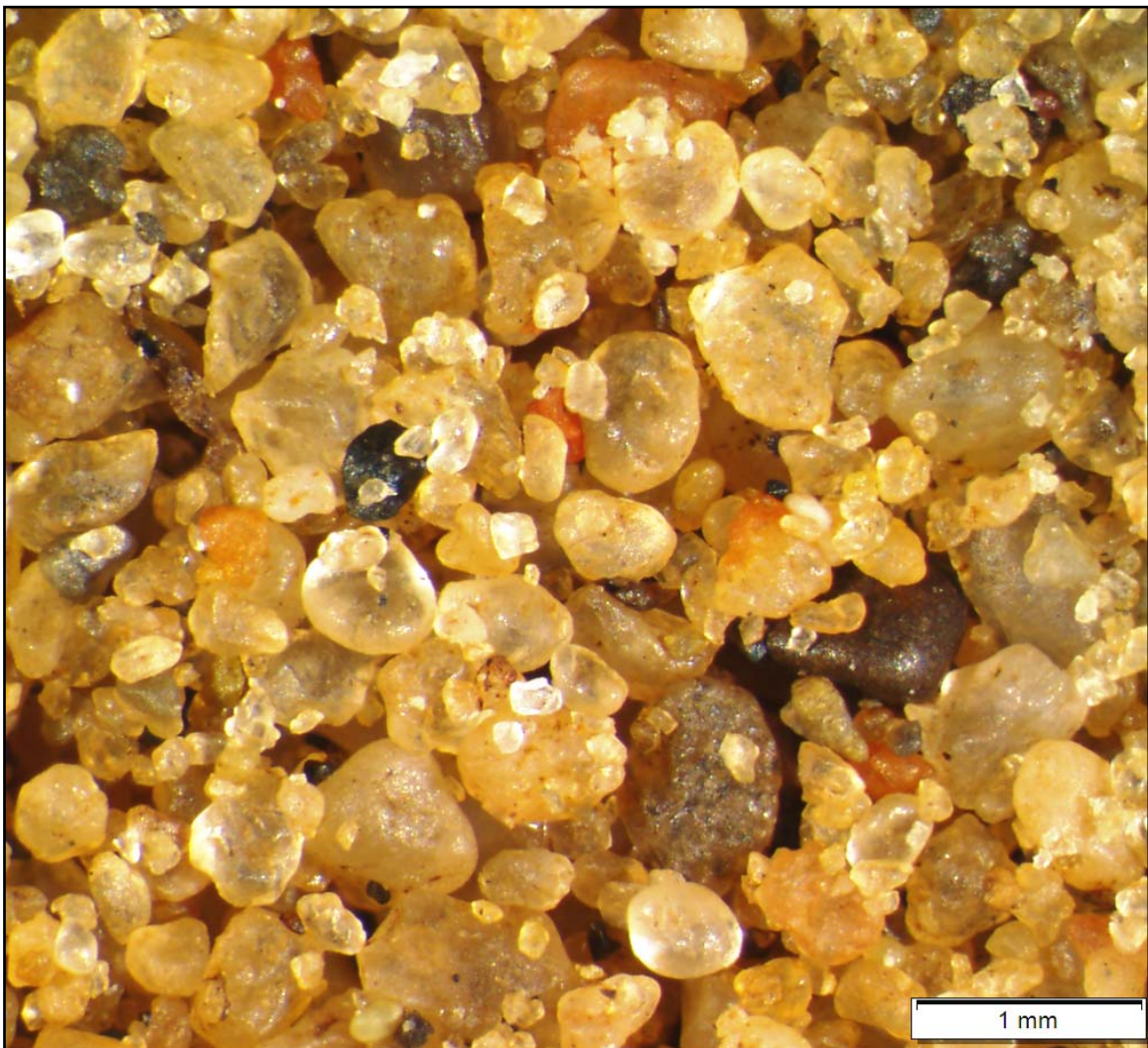


**INVESTIGATION OF SAND RESOURCES IN NORTH DAKOTA:
SEDIMENTOLOGICAL CHARACTERIZATION OF SURFICIAL
SAND DEPOSITS FOR POTENTIAL USE AS PROPPANT**

By

Fred J. Anderson



**REPORT OF INVESTIGATION NO. 110
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
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North Dakota Geological Survey

North Dakota Department of Mineral Resources

Mailing Address: 600 East Boulevard, Bismarck, ND 58505

Office Location: 1016 East Calgary Avenue, Bismarck, ND 58503

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On the cover: Photomicrograph (25x) of eolian sand from the Denbigh Dunes area (Sample No. 3 this report) in northeastern McHenry County, North Dakota.

TABLE OF CONTENTS

Acknowledgements	iv
Author's Note	iv
Executive Summary	v
BACKGROUND	1
Introduction	1
SAND RESOURCES IN NORTH DAKOTA	2
Location and Distribution	2
Sandstones within Sedimentary Bedrock Formations	3
Glaciofluvial Sands	4
Glaciolacustrine Sands	7
Eolian Sands	8
Fluvial Sands	11
SAMPLE COLLECTION METHODOLOGY	13
Description of Sample Collection	13
Samples Collected from Private Landowners	13
Samples Collected from Industry Producers	13
Samples Collected based on Geological Origin	15
DESCRIPTION OF TESTING RESULTS	16
Sample Preparation	16
Particle Size Distribution – Textural (Sieve Analysis)	16
% Clusters	22
Sand Grain Morphology (Sphericity and Roundness)	22
Acid Solubility	27
Silt and Clay Fines (Turbidity)	27
Crush Resistance	27
Mineralogy (X-Ray Diffraction)	30
Silicates	35
Carbonates	35
Iron-Bearing Minerals	35
Clays	35
Bulk Density	35
Specific Gravity (Apparent Density)	35
CONSIDERATIONS FOR SAND PROCESSING	36
CONCLUSIONS	38
REFERENCES	39
APPENDICES	40
Appendix I. Proppant Testing Specifications and Recommendations	41
Appendix II. Individual Bulk Grain Size Distribution Diagrams for Selected Sand Samples	42
Appendix III. Individual Grain Size Distribution Diagrams for Selected Sized Sand Samples	53
PLATES	64

LIST OF TABLES

Table 1. Selected Sand Samples Submitted for Testing Location Summary.....	vi
Table 2. Proppant Testing Analytical Summary – Selected Sands in North Dakota.....	vii
Table 3. Locations and areas of selected dune areas found in North Dakota	8
Table 4. Selected Sand Samples Location and Description Summary	14
Table 5. Calculated % Fines Loss on Sample Preparatory Wash.....	17
Table 6. Bulk Composite Sample Sieve Analysis Results (Weight Percent Retained)	18
Table 7. Selected Sized Sample Sieve Analysis Results (Weight Percent Retained).....	20
Table 8. Bulk Composite Sample Sieve Analysis Results (Percent In-Size).....	23
Table 9. Grain-Size Distribution Engineering Statistics Summary	24
Table 10. Crush Resistance Testing Summary	31
Table 11. Detailed X-Ray Diffraction Mineralogy Analyses on Selected Samples (Clay and Bulk).....	32

LIST OF FIGURES

Figure 1. Locations of surficial sand resources and selected samples.....	v
Figure 2. Bulk grain-size distribution curves for selected samples	vi
Figure 3. Bulk XRD mineralogical composition of selected samples	viii
Figure 4. Illustration of the steps in the process of developing a sand resources for use as proppant.....	1
Figure 5. Locations of recent sand and gravel production in North Dakota	2
Figure 6. Sandstone outcrop of the Bullion Creek Formation in northern Burleigh County	3
Figure 7. Location and distribution of bedrock formations containing sandstones	3
Figure 8. Location and distribution of glaciofluvial sands in North Dakota	4
Figure 9. Glaciofluvial sands and gravels deposited in the Verendrye diversion channel.....	4
Figure 10. Bulk sample photomicrograph of glaciofluvial sand near Velva	5
Figure 11. Sand and gravel terrace deposits in the Souris River Valley at Minot	6
Figure 12. River terraces in the James River Valley.	6
Figure 13. Aerial image of classical Glacial Lake Agassiz beach landforms.	7
Figure 14. Bulk sample photomicrograph of glaciolacustrine sand from south-central Grand Forks Co.....	7
Figure 15. Areas in North Dakota where eolian sands occur in dune deposits.....	8
Figure 16. Grain size distributions of selected dune sands in North Dakota	9
Figure 17. Bulk sample photomicrograph of eolian sand from the Sheyenne Dunes.....	9
Figure 18. Photograph of high-relief sand dune in the Brampton Dunes area.....	10
Figure 19. Modern fluvial sand bar deposits in the Missouri River channel south of Bismarck	11
Figure 20. Grain-size distribution curves of sands collected from selected North Dakota rivers.....	11
Figure 21. Bulk sample photomicrograph (25x) of fluvial channel sands of the Sheyenne River.....	12
Figure 22. Bulk sample grain size distribution curves of sands selected for testing as proppants.....	19
Figure 23. Sized sample grain size distribution curves of sands selected for testing as proppants.....	21
Figure 24. Standard (25x) photomicrographs of tested sand samples	25
Figure 25. Recommended proppant particle shape factors chart.....	26
Figure 26. Comparison of acid solubility test results for tested sand samples	28
Figure 27. Comparison of sand sample turbidity test results.....	28
Figure 28. Results of crush resistance testing and % fines generated for tested sand samples.....	29
Figure 29. Summary of X-Ray Diffraction mineralogical analyses completed on tested samples.....	33
Figure 30. Detailed X-Ray Diffraction analyses results completed on tested samples.....	34
Figure 31. Comparison of tested sand densities (apparent and bulk)	34
Figure 32. Possible sand & gravel plant natural sand proppant processing flowsheet	37

LIST OF FIGURES (Contd.)

Figure A-II-1. Bulk Sample Grain-Size Distribution Diagram for Sample No. 1 - Qod.....43
Figure A-II-2. Bulk Sample Grain-Size Distribution Diagram for Sample No. 2 - Qcrh.....44
Figure A-II-3. Bulk Sample Grain-Size Distribution Diagram for Sample No. 3 - Qtou.....45
Figure A-II-4. Bulk Sample Grain-Size Distribution Diagram for Sample No. 4 - Qtu.....46
Figure A-II-5. Bulk Sample Grain-Size Distribution Diagram for Sample No. 5 - Tb47
Figure A-II-6. Bulk Sample Grain-Size Distribution Diagram for Sample No. 6 - Tb48
Figure A-II-7. Bulk Sample Grain-Size Distribution Diagram for Sample No. 7 - Qcrf.....49
Figure A-II-8. Bulk Sample Grain-Size Distribution Diagram for Sample No. 8 - Qcew.....50
Figure A-II-9. Bulk Sample Grain-Size Distribution Diagram for Sample No. 9 - Qcdn51
Figure A-II-10. Bulk Sample Grain-Size Distribution Diagram for Sample No. 10 - Tc.....52

Figure A-III-1. Grain-Size Distribution Diagram for Sample No. 1 – Qod.....54
Figure A-III-2. Grain-Size Distribution Diagram for Sample No. 2 – Qcrh 30/50 Cut.....55
Figure A-III-3. Grain-Size Distribution Diagram for Sample No. 3 – Qtou 30/50 Cut.....56
Figure A-III-4. Grain-Size Distribution Diagram for Sample No. 4 – Qtu 30/50 Cut.....57
Figure A-III-5. Grain-Size Distribution Diagram for Sample No. 5 – Tb 30/50 Cut58
Figure A-III-6. Grain-Size Distribution Diagram for Sample No. 6 – Tb 30/50 Cut59
Figure A-III-7. Grain-Size Distribution Diagram for Sample No. 7 – Qcrf 30/50 Cut60
Figure A-III-8. Grain-Size Distribution Diagram for Sample No. 8 – Qcew 30/50 Cut61
Figure A-III-9. Grain-Size Distribution Diagram for Sample No. 9 – Qcdn 30/50 Cut62
Figure A-III-10. Grain-Size Distribution Diagram for Sample No. 10 – Tc 40/70 Cut.....63

LIST OF PLATES

Plate I. Sand Resources and Sample Locations 65
Plate II. Photomicrograph (25x) Examples of Selected Sand Sources in North Dakota 66
Plate III. Field Sand & Gravel Grab Sample Photographic Summary.....67

LIST OF ABBREVIATIONS

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

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The author would like to thank all of the private landowners throughout the state, who allowed and facilitated access to their properties for sample collection over the course of this investigation, and to acknowledge the members of the N.D. sand and gravel producers industry: Northern Improvement Co., Strata Corporation, and Abrasives, Inc., whom also submitted several samples for consideration during this investigation. Also, to thank the members of the NDGS field geologic technician staff for their efforts and contributions during the 2009 summer field season, and Mr. Elroy Kadrmas, NDGS GIS Specialist, for cartographic design support. Comments and criticisms which also improved this work were also provided by Mr. Jeff Person, NDGS Paleontologist, and Mr. Edward C. Murphy, N.D. State Geologist.

Author's Note

The intent of this investigation was to characterize selected sand sources in North Dakota for potential use as natural sand proppants by using applicable testing methodologies recommended for the testing and evaluation of natural sands as proppants as published by ISO, ANSI, API and current practice in the oil and gas industry. Proppant testing services were provided by Stim-Lab, Inc., Duncan, Oklahoma.

Executive Summary

An investigation into the potential use of sands found in North Dakota as natural proppants for use in the hydraulic fracturing of oil and gas wells in the Williston Basin was conducted during the 2009-2011 biennium. The intent of this investigation was to characterize selected sand sources for potential use as proppants by using applicable testing methodologies recommended for the testing and evaluation of natural sands as proppants as published by the International Organization for Standards (ISO), the American National Standards Institute (ANSI), and the American Petroleum Institute (API), and current oil and gas industry engineering practice. Selected sand samples were obtained from private landowners, members of the sand and gravel producing industry, and by the N.D. Geological Survey (NDGS) from sand sources across North Dakota (Figure 1) in the Oahe Formation (Holocene), Coleharbor Group (Pleistocene), and Bullion Creek Formation (Paleocene). Ten samples, representing a broad variety of sand types found in the state were submitted for testing and characterization for potential use as natural proppant sands (Table 1). Test results included the: determination of grain-size distribution via sieve analysis on bulk (Figure 2) and selected sized samples, determination of sand crush resistance and HCL-HF acid solubility, determination of particle shape factors of individual grain sphericity and roundness, sand sample turbidity, and sand density determinations including bulk and apparent (i.e. specific gravity) densities. Overall, testing indicated fines, the percent loss on sample preparatory wash from bulk samples, from 4.1 to 30%. Testing and analysis results on eight prepared 30/50 and two 40/70 sized samples indicated crush resistance values ranging from <2,000 to 5,000 psi, HCL-HF acid solubility ranging from 5.9 to 56.8%, average sphericity and roundness values of 0.6 and 0.56, respectively, International Organization for Standardization (ISO) mean particle diameters ranging from 0.239 to 0.465 mm, median particle diameters ranging from 0.236 to 0.455 mm, turbidities ranging from 8 to 85 Formazin Turbidity Units (FTU), with bulk densities ranging from 75.5 to 91.7 pcf with an average specific gravity of 2.63 g/cm³. Four of the ten samples tested reported percent clusters at ~1/100 (Table 2). X-Ray Diffraction (XRD) mineralogical analyses completed on five of the ten samples reported total clays ranging from 1 to 14% with smectite being the dominant clay mineral (Figure 3). Total silicates range from 81 to 98% with quartz ranging from 45 to 68%. Total carbonates range from 1 to 16% with dolomite ranging from 4 to 10%, and iron minerals reported from trace amounts up to 1%.

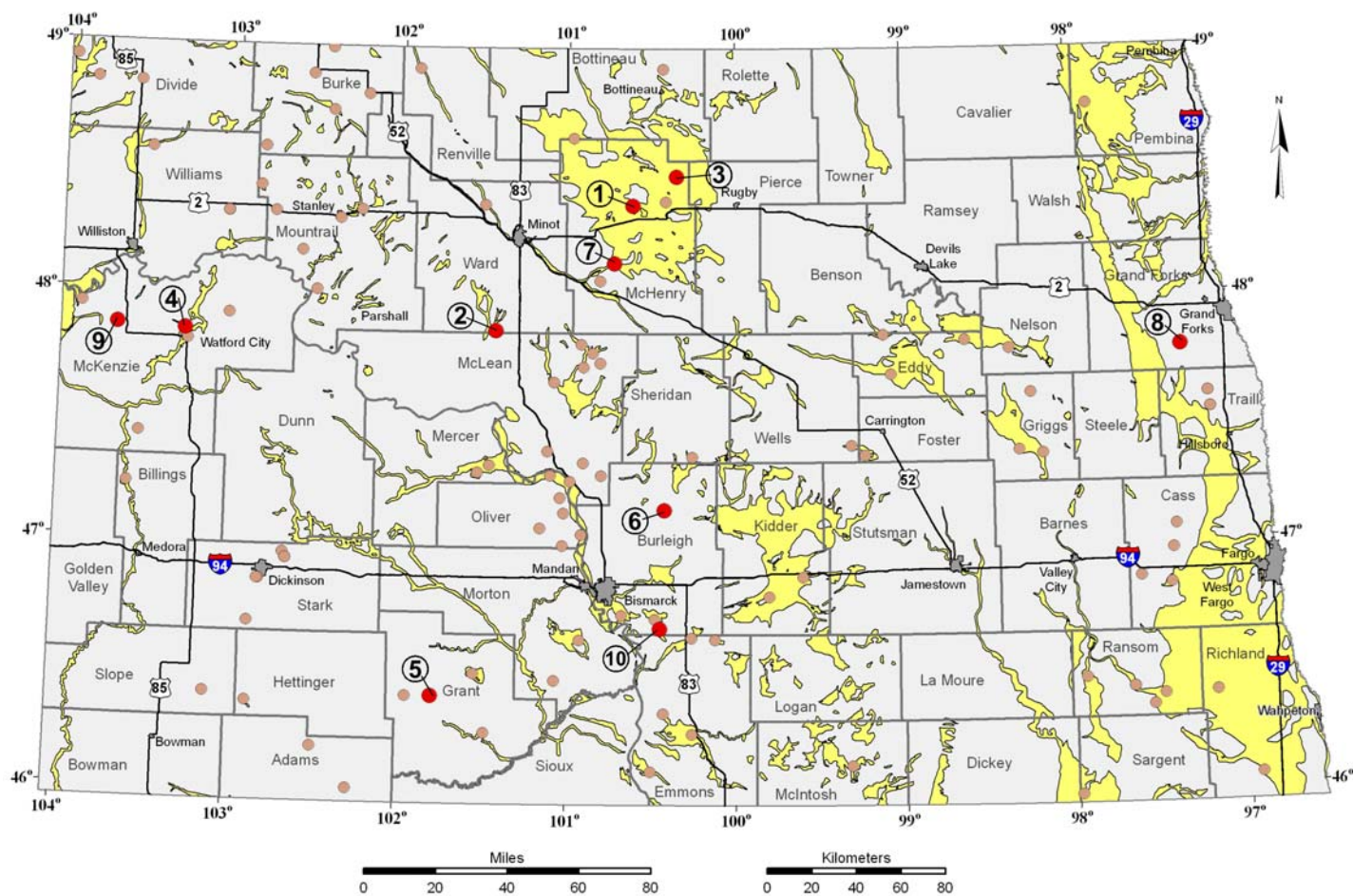


Figure 1. Locations of N.D. surficial sand resources (yellow) along with the locations of sand sources sampled throughout the state (brown circles) as a part of this investigation along with the locations of selected sand samples submitted for testing and characterization for potential use as proppant (numbered red circles).

Table 1. Location and Description Summary of Selected Sand Samples Submitted for Testing.

No.	County	Location (T., R., Sec.)	Geologic Map Unit	Geologic Map Unit Description
1	McHenry	156-77-6	Qod	Windblown sand (Holocene)-Well-sorted, medium sand with obscure bedding; poorly developed paleosols common; as thick as 30 feet; knobby topography consisting of inactive transverse or longitudinal dunes nearly obliterated by more recent blowouts.
2	Ward	151-84-33	Qcrh	Collapsed river sediment-(Holocene to Pre-Wisconsinan)-Moderately well sorted cross-bedded sand and plane-bedded gravel, including sediment of melt-water and other rivers; as thick as 100 feet, faulted and contorted supraglacial sediment with hummocky topography.
3	McHenry	158-75-28	Qtou	Sand of the Oahe and older Formations, undivided (Holocene to Pliocene)-Windblown sand of the Oahe Formation, as thick as 10 feet, and sand of older formations with an undulating wind-scoured surface.
4	McKenzie	150-99-1	QTu	Quaternary and Upper Tertiary Sediment, Undivided-Largely river sediment; includes upper Quaternary terrace, fan, and pediment derived material such as sandstone, silicified wood, and concretions and Pliocene(?) to middle(?) Quaternary clay, silt, sand, and gravel composed of rounded pebbles and cobbles of quartzite and porphyry derived from the Black Hills or Rocky Mountains; as thick as 300 feet.
5	Grant	134-88-31	Tb	Bullion Creek Formation (Paleocene) - Yellow-brown silt, sand, clay, sandstone, and lignite; river, lake and swamp sediment as thick as 600 feet.
6	Burleigh	142-77-10	Tb	Bullion Creek Formation (Paleocene) - Yellow-brown silt, sand, clay, sandstone, and lignite; river, lake and swamp sediment as thick as 600 feet.
7	McHenry	154-78-29	Qcrf	Uncollapsed river sediment-flat-bedded sediment of gently sloping plains and terraces, commonly with braided-channel scars.
8	Grand Forks	150-52-29	Qcew	Wave-Eroded glacial sediment-glacial sediment with flat to gently undulating topography resulting from wave erosion; covered by a thin gravel lag in places.
9	McKenzie	151-102-35	Qcdn	Draped glacial sediment-Thin glacial sediment draped over and only slightly modifying the non-glacial topography existing before the last glacial advance.
10	Burleigh	137-77-30	Tc	Cannonball Formation (Paleocene)-Olive-brown sand, shale, and sandstone; marine shoreline and offshore sediment; as thick as 400 feet.

Geologic map unit descriptions from the Geologic Map of North Dakota (Clayton et al., 1980).

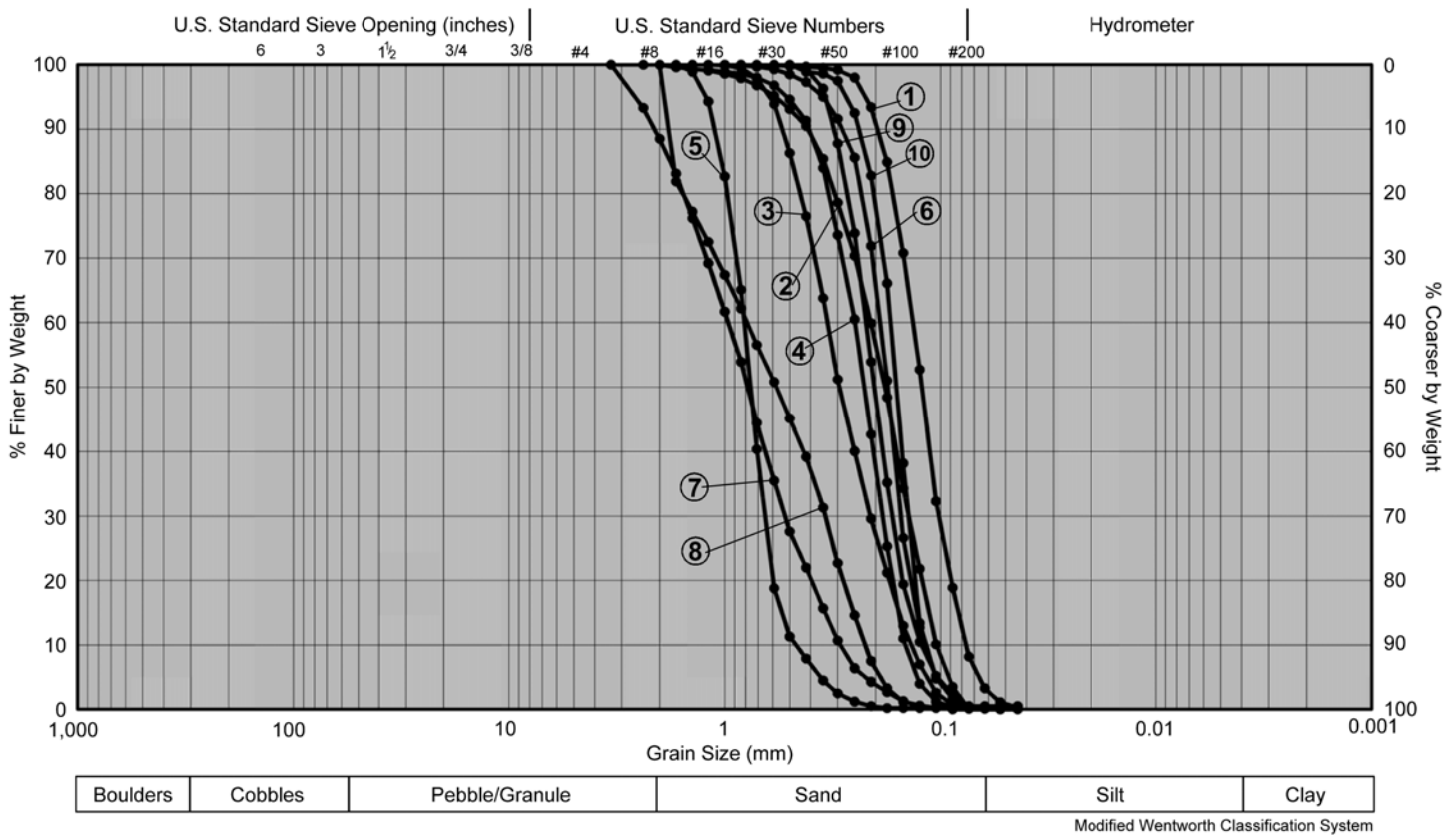


Figure 2. Bulk sample grain-size distribution curves for the ten N.D. sand samples tested and characterized for potential use as proppant. Each curve is labeled with the corresponding sample number.

Table 2. Proppant Testing Analytical Summary - Selected Sands in North Dakota.

Sample No.	Tested Size Cut	Crush Resistance (K-Value)	Acid Solubility (%)	Sphericity	Roundness	ISO Mean Particle Dia. (mm)	Median Particle Dia. (mm)	Turbidity (FTU)	% Clusters	Bulk Density (g/cm ³)	Bulk Density (pcf)	Specific Gravity (g/cm ³)
1	40/70	<2K	16.6	0.6	0.5	0.239	0.236	85	~1/100	1.23	76.8	2.58
2	30/50	4K	6.4	0.7	0.6	0.394	0.386	8	NIFC	1.44	89.9	2.63
3	30/50	5K	6.4	0.6	0.5	0.428	0.418	18	NIFC	1.44	89.9	2.65
4	30/50	2K	10.7	0.6	0.6	0.388	0.380	20	NIFC	1.33	83.0	2.63
5	30/50	5K	5.9	0.6	0.6	0.465	0.455	16	NIFC	1.47	91.7	2.62
6	30/50	<2K	56.8	0.6	0.6	0.383	0.374	36	~1/100	1.07	66.8	2.68
7	30/50	4K	17.1	0.6	0.6	0.443	0.433	25	~1/100	1.41	88.0	2.67
8	30/50	4K	13.7	0.6	0.6	0.421	0.411	28	~1/100	1.41	88.0	2.64
9	30/50	<2K	7.9	0.6	0.5	0.367	0.362	10	NIFC	1.32	82.4	2.62
10	40/70	<2K	8.9	0.6	0.5	0.245	0.243	72	NIFC	1.21	75.5	2.61

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

FTU = Formazin Turbidity Unit.

NIFC = No clusters observed in field of count.

pcf = pounds per cubic foot.

Proppant testing services were provided by Stim-Lab, Inc., Duncan, Oklahoma. Current testing specifications and recommendations for natural sand proppants, characterized for use in the hydraulic fracturing of oil and gas wells, are summarized below and include the following parameters:

Grain-Size Distribution (Sieve Analysis) - It is recommended that a minimum of 90% of tested sand fall between 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). All selected sized samples (i.e. 40\70, 30\50) tested met this criterion.

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). Reported K-values are all dominantly less than 5K with five samples (No. 1, 4, 6, 9 & 10) returning values of 2K or less. 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. Samples 2, 3, 5, 7 & 8 met this criterion.

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” present 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 2% (by weight) HCL-HF soluble constituents, and for sands sized in the range from 40/70 to 70/140 contain no more than 3% (by weight) HCL-HF soluble constituents. None of the samples tested met this criterion.

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. Sample Nos. 1, 3, 9, and 10 were near but did not meet this criteria. Percent clusters are recommended to be less than 1\100 within the field of count.

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

Mineralogy - In order to provide an understanding of overall mineralogical character of tested sand that is being evaluated for use as a proppant, a qualitative mineralogical analysis by X-ray diffraction (XRD) methods is recommended (Figure 3). Evaluations of relative peak heights are to be used to estimate the amount of clays present, in addition to the reporting of any minerals found at levels above about one percent. For comparison, quartz percentages for Ottawa “white” type sands are commonly around 99%.

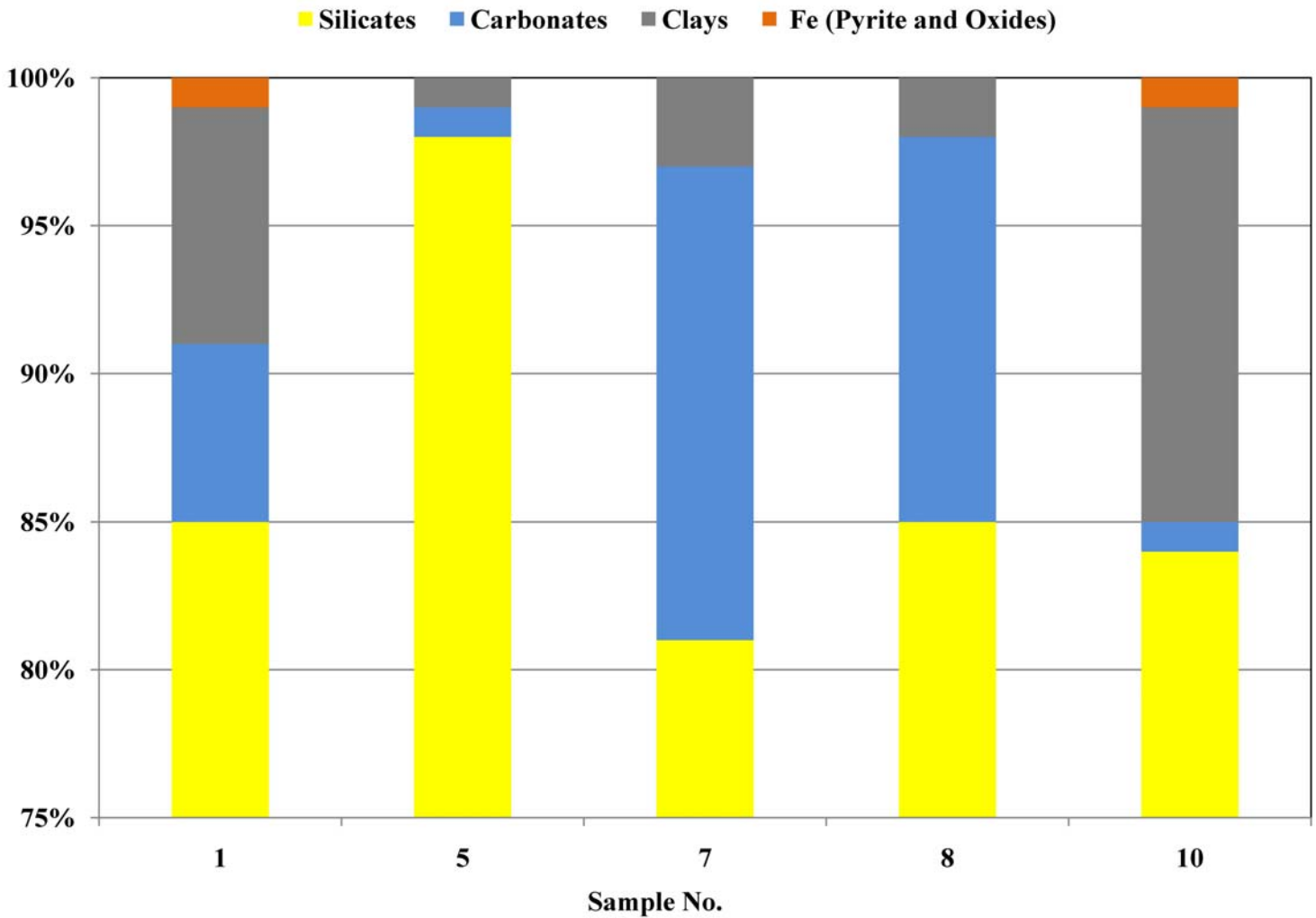


Figure 3. Bulk mineralogical composition of selected sand samples as determined from X-Ray Diffraction (XRD) analyses.

Based on the results of the sand testing and characterization work completed during this investigation, it is concluded that the production of usable quantities of natural sands from tested sources for use as proppant, would likely require several mechanical processing and chemical refinement steps (with anticipated high amounts of bulk volume loss) in order to produce viable amounts of natural sand proppant. The information contained in this report will be beneficial in the continued characterization and evaluation of sand (and gravel) resources for use in other industrial applications. It should be noted that the consideration of a “multiple markets approach” in the development of North Dakota’s mineral resources is beneficial and fosters good stewardship of our natural resources.

BACKGROUND

Introduction

The continued success of the Bakken\Three Forks oil play in North Dakota, through the hydraulic fracturing of oil and gas wells and placement of proppants in fractures during the stimulation of completed wells, has created an unprecedented demand for natural proppants in the Williston Basin. It has been estimated that the demand for proppants will be in the millions of tons and potentially billions of dollars, in order to fully develop all the Bakken\Three Forks reservoirs in the state. Currently, natural sand proppants are being imported from locations across the globe and include foreign sources from China, Russia, South America, and Canada. The need to evaluate domestic, and more importantly, local resources with a potential to meet the growing demand for natural sand proppants is a timely and prudent geological investigative activity.

The North Dakota Geological Survey (NDGS) conducted an investigation of North Dakota's sand resources for potential use as natural proppants in the hydraulic fracturing of oil and gas wells in the Williston Basin during the 2009-2011 biennium. During this investigation, members of the public and of the sand and gravel production industry in North Dakota were engaged and encouraged to submit samples from their respective deposits of interest to be evaluated and potentially tested for characterization as a natural sand proppant.



Figure 4. Illustration of several of the steps in the production of a sand resource for use as a proppant: a. identification and mapping of potential sand resources in the field, b. contemporary sand and gravel processing operation, c. bulk transfer facility from rail delivery to truck transport, d. staging proppants in distribution areas for transport to the well site, e. rail cars of proppant sand and frac tanks staged on the well pad.

SAND RESOURCES IN NORTH DAKOTA

Location and Distribution

North Dakota's surficial sand (and gravel) resources can be found across 73 percent of the state, dominantly in the glaciated central and eastern portions, and cover an approximate 51,256 square miles (~33 million acres) area. Based on previous NDGS geologic mapping work completed across the state, sand resources are dominantly found in areas previously occupied and modified by glacial ice and resultant meltwaters and along major fluvial (river) systems such as the Souris and Missouri Rivers and within the consolidated sedimentary bedrock units found in southwestern North Dakota (Figure 2). Areas in North Dakota, previously occupied by glacial lakes, such as Glacial Lake Souris in north-central North Dakota and Glacial Lake Agassiz in the Red River Valley of eastern North Dakota, contain the majority of localized surficial sand (and gravel) resources found in the state. Recent yearly production of sand (and gravel) resources in North Dakota, based on the information provided by members of the sand and gravel producing industry that report annual production, was reported to be 3.9 million cubic yards in 2010 (NDSSCC, 2011) which was dominantly from the northwestern part of the state in the Souris River Valley region and west into southern Williams and northern McKenzie counties and in south-central North Dakota in Burleigh, Kidder, and Logan counties (Figure 5).

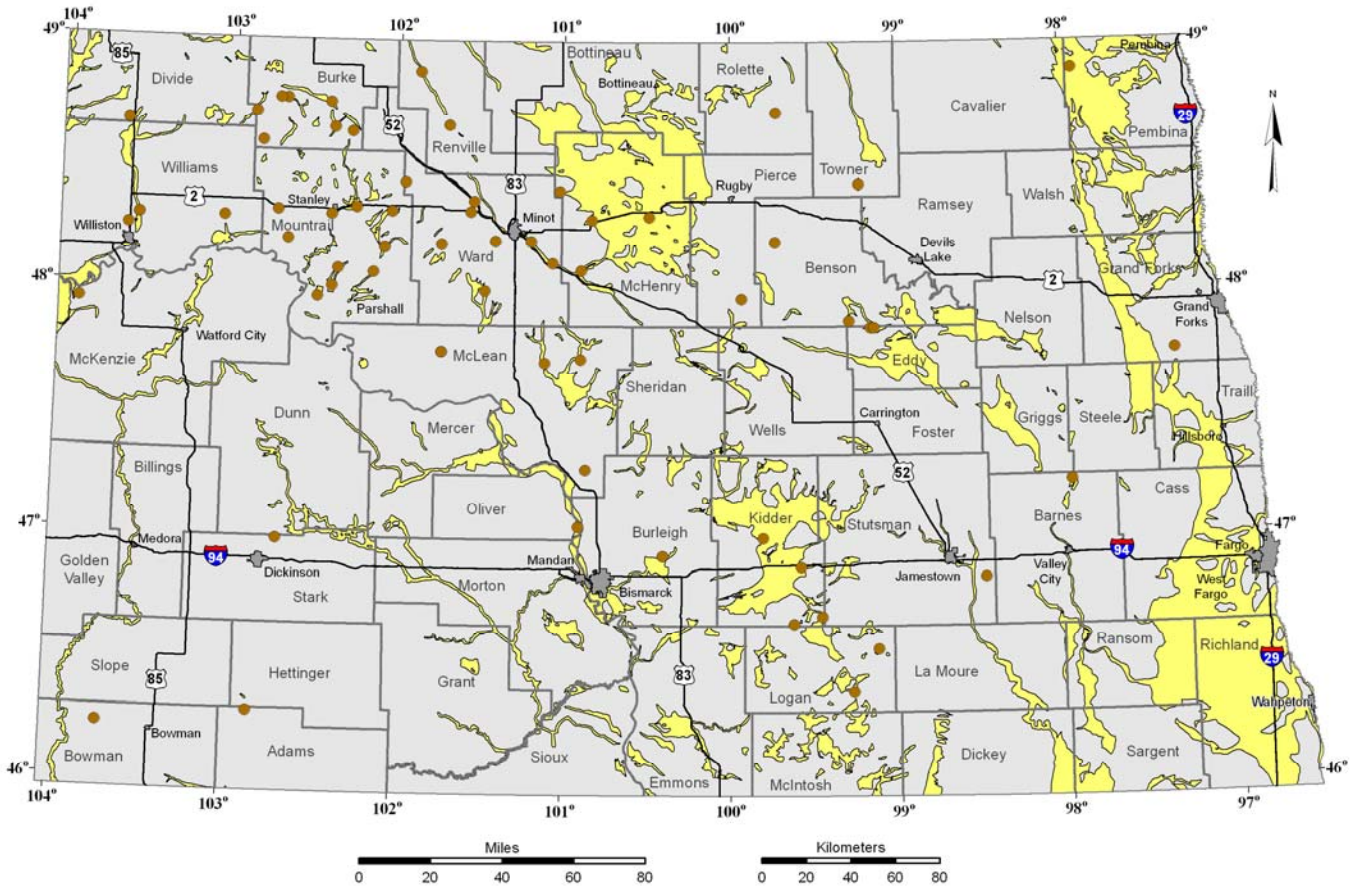


Figure 5. Areas in North Dakota where surficial sand (and gravel) resources are found with the locations of recent (2010) reported sand and gravel production (brown circles) shown.

Sandstones within Sedimentary Bedrock Formations

The geologically oldest sand resources that occur in North Dakota can be found within the consolidated sedimentary bedrock formations present across 28 percent of the state that cover an area of approximately 18,910 square miles (~12 million acres) in southwestern North Dakota. Sand is present in discrete sandstone units within the Cretaceous age Hell Creek and Fox Hills Formations, the early Tertiary age Ludlow, Cannonball, and Slope Formations, and the late Tertiary Bullion Creek (Figure 6), Sentinel Butte, and Golden Valley Formations (Figure 7). Three samples were collected and submitted for testing from these units. Sample Nos. 5 and 6 were collected from the Bullion Creek Formation in northern Burleigh County and west-central Grant County, respectively. Sample No. 10 was collected from the Cannonball Formation in southern Burleigh County (Figure 1).



Figure 6. View to the north of a well-cemented sandstone outcrop of remnant sedimentary bedrock of the Bullion Creek Formation, located in northern Burleigh County, just east of Regan. Outcrops similar to these can be found throughout the western two-thirds of Burleigh County.

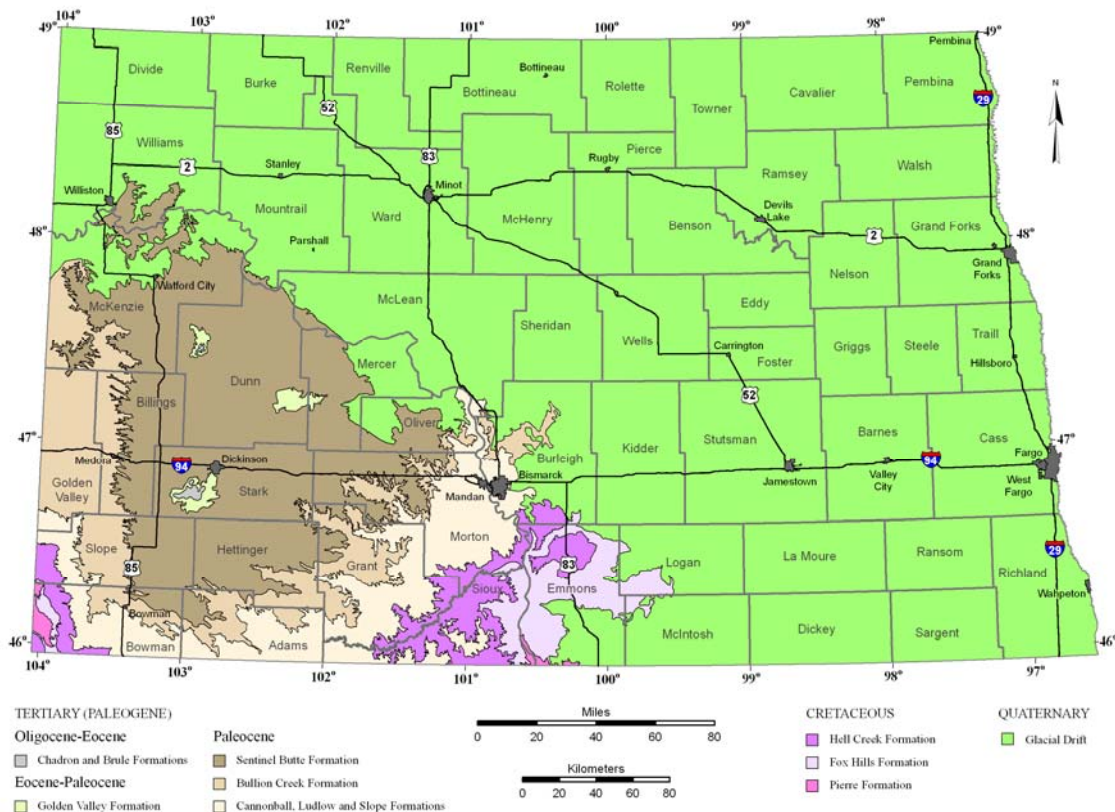


Figure 7. Location and distribution of exposed sedimentary bedrock formations containing sandstones of Cretaceous and Tertiary age that contain appreciable amounts of sands in North Dakota. The extent of the state covered by glacial sediments is collectively shown in green.

Glaciofluvial Sands

Flowing glacial meltwaters have also deposited sand and gravel across the state's glaciated landscape (Figure 8). These glaciofluvial sands occur within glacial outwash deposits of sand and gravel and meltwater channel deposits (Figure 9) that cover 2,919 square miles (1.9 million acres). These deposits are located dominantly across south and east-central North Dakota and consist dominantly of stratified sand and gravel deposits ranging in thickness of up to 100 feet (Clayton, 1980; Murphy, 2000).

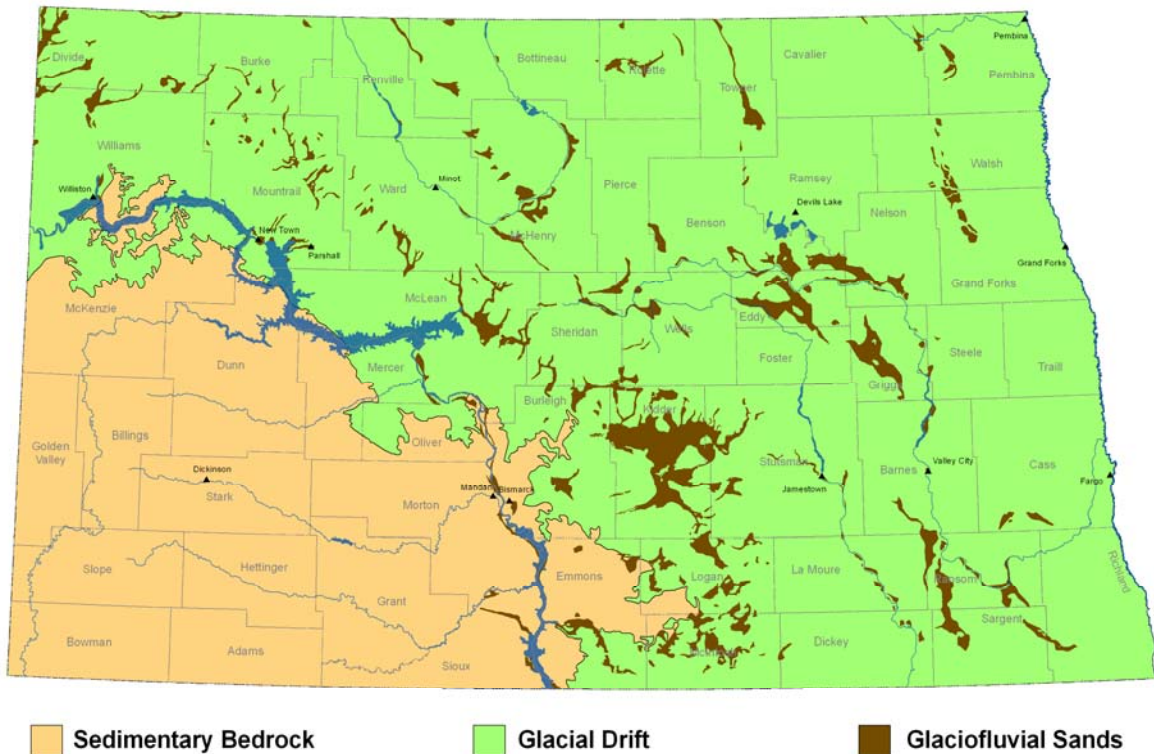


Figure 8. Location of sand (and gravel) deposits associated with glaciofluvial processes in North Dakota (shown in brown).



Figure 9. Glaciofluvial sand and gravel deposited along the former Verendrye glacial meltwater diversion channel located southeast of Velva, North Dakota. View is to the north from State Highway 2. Recent exposures and sloughing within the sand deposits is visible along the valley slopes north of the rail line which traverses the channel axis southeast from Velva towards Verendrye, North Dakota.

Glaciofluvial sands can be found in central and northwestern McHenry County (Figure 10), along the margins of deposits formed from the presence of the former Glacial Lake Souris (Bluemle, 1982; Lord, 1988) and along former glacial meltwater drainageways in east-central North Dakota associated with the post-glacial James and Sheyenne rivers in Eddy, southeastern Benson and western Nelson, and western Griggs Counties. Glaciofluvial sands can also be found in broad glacial outwash plains consisting of stratified sand and gravel in south-central North Dakota, dominantly in Kidder County, approximately 40 miles east of Bismarck. The outwash deposits located in Kidder County occupy an area of around 350 square miles (Rau et.al. 1962). Samples No. 2 and 7 were collected from these types of sediments, in southern McHenry County and southern Ward County, respectively. For the purposes of this report, sand and gravel deposits occurring within the larger mapped river terraces are grouped and described within the glaciofluvial sands section discussed here rather than in the fluvial sands section based upon their geologic origins as glacial meltwater deposits.



Figure 10. Bulk sample photomicrograph (25x) of glaciofluvial sand from the Verendrye glaciofluvial meltwater diversion channel southeast of Velva, North Dakota.

The range of particle sizes found in these types of deposits range from clay fines to sand and gravel to cobbles and large boulders which commonly occur in older glaciofluvial terrace deposits (Figure 11) found adjacent to the valley walls within major drainageway.



Figure 11. Sand and gravel terrace deposit along the northern margin of the Souris River Valley in northeastern Ward County, on the western edge of Minot, North Dakota. The range of glaciofluvial sediment sizes, dominantly sand and gravel, with a smaller percentage of cobbles is common in these types of deposits.

The majority of sand and gravel production that occurs in North Dakota often occurs within and along the floodplains of North Dakota's major river systems. An abundance of localized sand and gravel deposits can be found commonly within river terrace landforms (Figure 12) that occur along the edges of the relatively broader river floodplains. Produced sand is processed for a variety of uses ranging from construction sand and gravel to playground sand. Consideration of deposit variability and the potential for multiple end uses and markets may be worthwhile when evaluating these particular types of sand and gravel resources across the state.

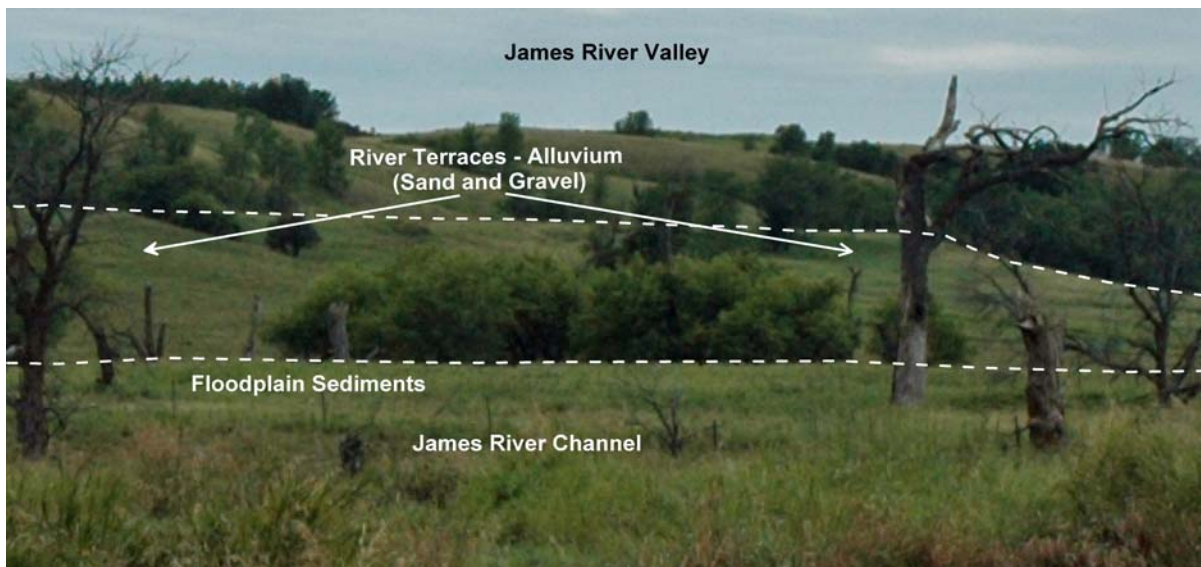


Figure 12. View to the southwest of river terraces along the James River Valley near Jamestown. The river terrace landform tops and contact with lower-lying floodplain sediments are highlighted by the dashed white line. The James River channel is present in the lower foreground.

Glaciolacustrine Sands

Sand deposits may also be found adjacent to areas formerly occupied by glacial lakes. These sands (and gravels) were deposited along the shorelines and deltas of the larger glacial lakes that were present in North Dakota during the Pleistocene-Holocene Epochs. These deposits are dominantly found in eastern North Dakota along the western margin of the Red River Valley (Plate I), resulting from the presence of Glacial Lake Agassiz (Figure 13), and in north-central North Dakota in the Souris River Valley in McHenry County, resultant from the presence of Glacial Lake Souris. Sample No. 8 (this report) was collected from the Campbell-McCaullyville beach deposits of the former Glacial Lake Agassiz in south-central Grand Forks County (Figure 14).

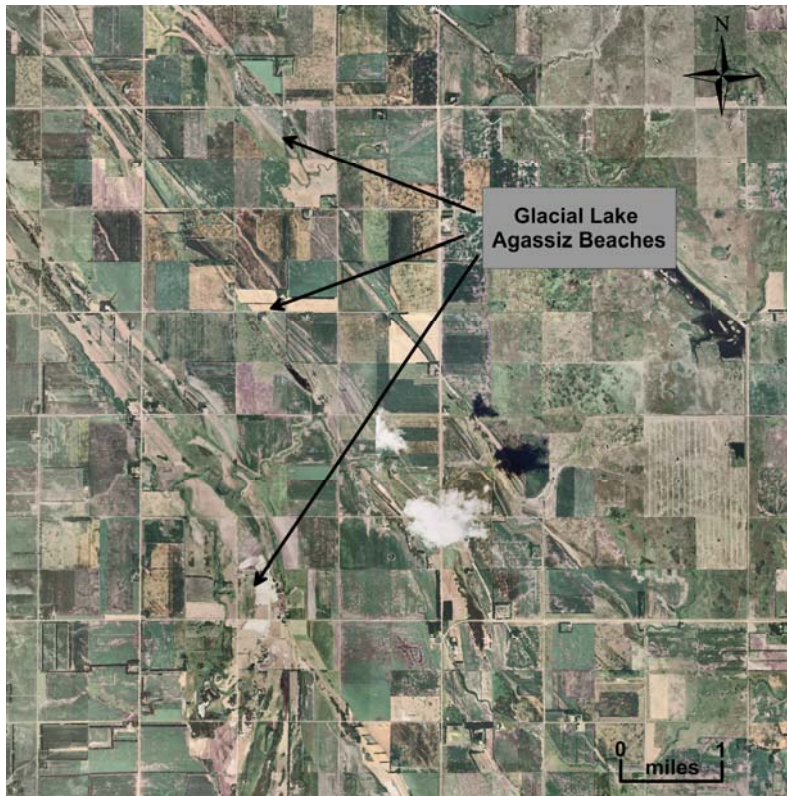


Figure 13. Classical aerial image (NAIP, 2006) of the linear beach landforms created by Glacial Lake Agassiz in south-central Grand Forks County. The beaches trend from the northwest to the southeast across the image. Thin deposits of sand and gravel can be found overlying subglacially derived sediments in these areas throughout the Red River Valley in eastern North Dakota.

Figure 14. Bulk sample photomicrograph (20x) of glaciolacustrine derived sand from the Campbell-McCaullyville beaches of Glacial Lake Agassiz in south-central Grand Forks County, North Dakota.



Eolian Sands

Eolian (windblown) sands occur across 3.8 percent of the state covering an area totaling 2,692 square miles (~1.7 million acres). These deposits are distributed dominantly in the eastern two-thirds of the glaciated portions of the state (Figure 15).

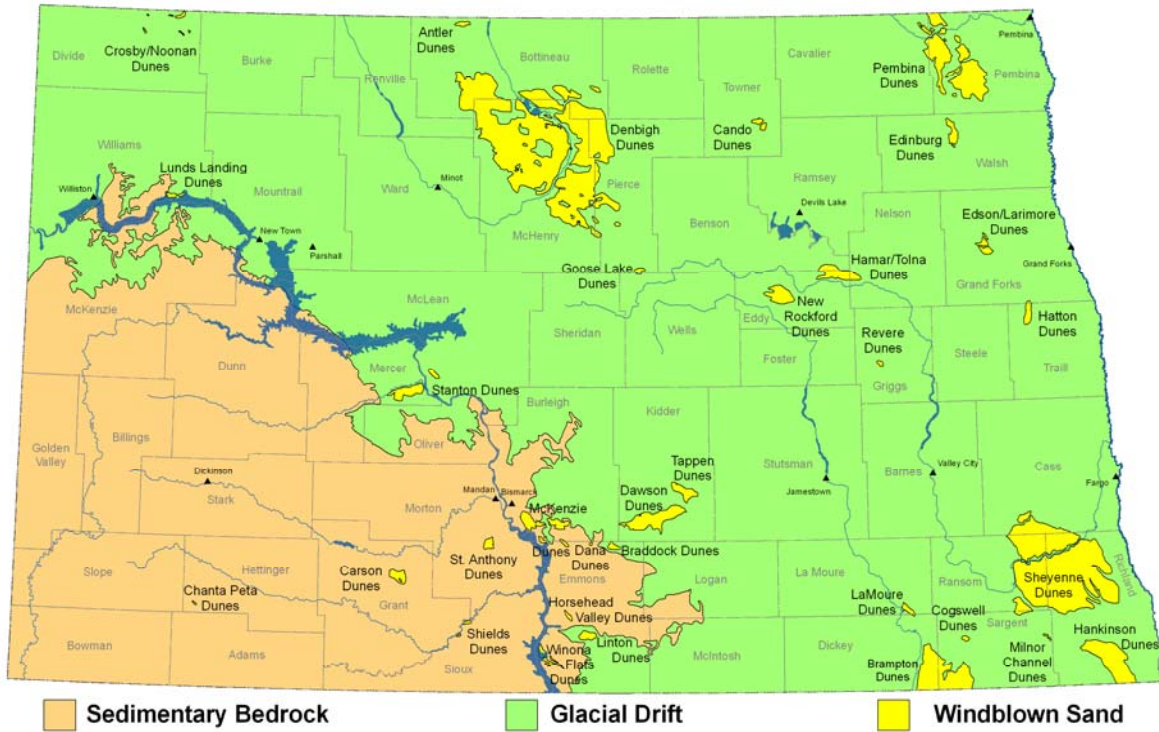


Figure 15. Areas in North Dakota where eolian (windblown) sands occur in dune deposits.

There are five areas where the expanse of eolian sand deposits is greater than 100 square miles and includes the: Denbigh Dunes in north-central North Dakota, Sheyenne, Hankinson, and Brampton (Riverdale Ridge) Dunes in southeastern North Dakota, and the Pembina Dunes in northeastern North Dakota (Table 3).

Table 3. Locations of selected dune areas found in North Dakota

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

Eolian sands found in North Dakota are well-sorted, fine to very-fine grained (Figure 16), with mineral compositions reflective of the localized glaciofluvial and glaciolacustrine deposits where they typically originate.

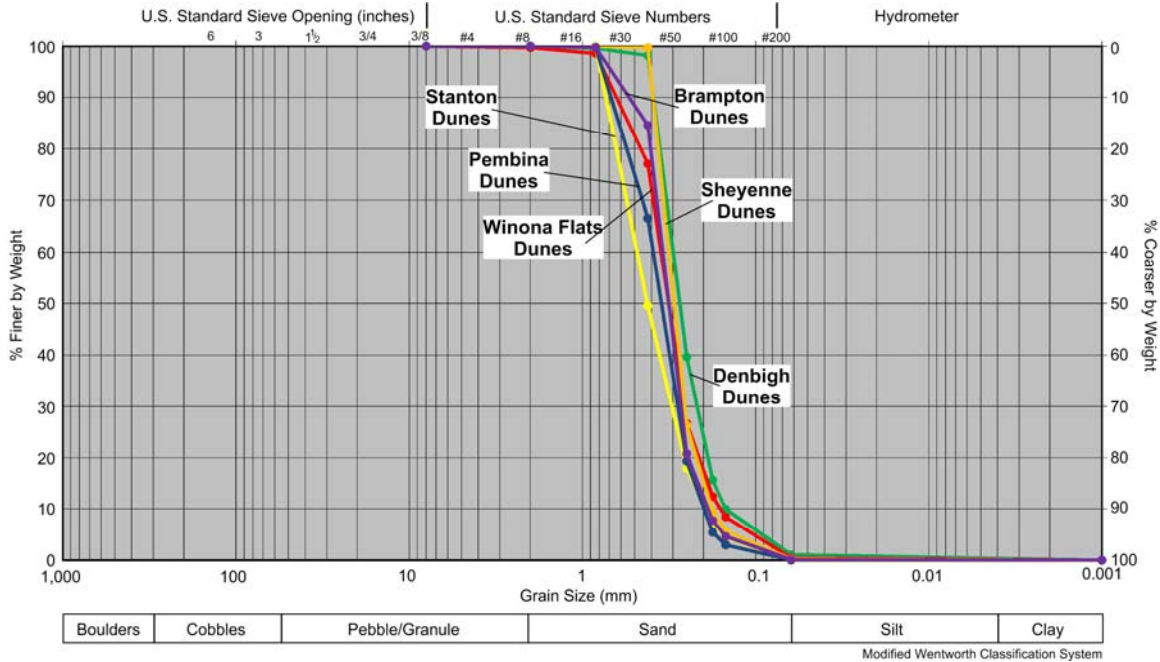


Figure 16. Grain-size distributions of selected dune sands in North Dakota. Grain sizes of the Brampton (Riverdale Ridge) area dunes (purple curve), Denbigh (green curve), Pembina (blue curve), Sheyenne (orange curve), Stanton (yellow curve), and Winona Flats Dunes (red curve) all plot within the medium to very fine sand size range.

The Denbigh Dunes, dominantly in McHenry County of north-central North Dakota, cover an area of 990 square miles and are the windblown remnants of sand and gravel deposits left behind from Glacial Lake Souris. Sample No. 1 was collected from a large stabilized dune approximately three and a half miles northwest of Denbigh (Figure 17).

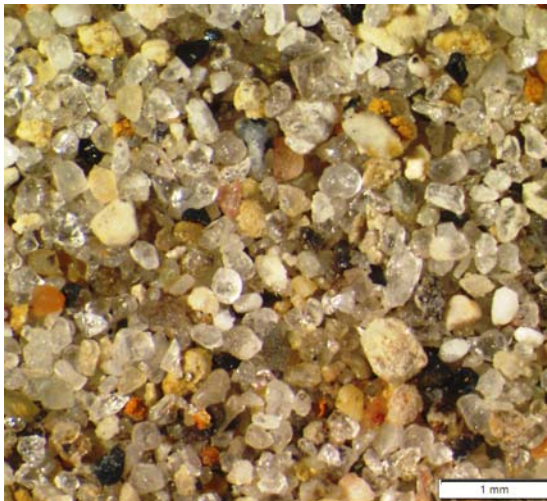


Figure 17. Bulk sample photomicrograph (25x) of eolian (windblown) sand (Sample No. 1, this report) from the Denbigh Dunes area in north-central McHenry County. The variety of mineralogical constituents contained within this deposit is readily apparent.

The Sheyenne Dunes, located in southeastern North Dakota in northwestern Richland, eastern Ransom, and southern Cass counties, cover an area of approximately 687 square miles. These dunes are the windblown accumulate of the sands deposited on the Sheyenne Delta (Figure 15) during the time when the Sheyenne River emptied into the southern end of Glacial Lake Agassiz around 12,000 thousand years ago (Arndt, 1977).

The Pembina Dunes, located in northeastern North Dakota in western Pembina County, cover an area of approximately 208 square miles. These eolian deposits (Figure 15) are the windblown accumulate of the sands deposited on The Pembina Delta, during the time when the Pembina River emptied into the northern end of Glacial Lake Agassiz in North Dakota, also around 12,000 thousand years ago (Arndt, 1977).



Figure 18. Large sand dune in the Brampton Dunes (Riverdale Ridge) area in southeastern North Dakota in western Sargent County. This dune is one of the larger and more visually impressive sand dunes found in North Dakota.

There are several additional areas in the state where eolian deposits can be found, such as the Riverdale Ridge portion of the Brampton Dunes area in southwestern Sargent County (Figure 18). These areas are relatively much smaller than the dune areas associated with the occurrence of deposits left behind near the margins of glacial lakes (i.e. Glacial Lakes Souris and Agassiz). Areal extents are significantly less than 100 square miles (Anderson, in prep.) and include the McKenzie Dunes in southwestern Burleigh County, the Hamar\Tolna Dunes in southeastern Ramsey, northeastern Eddy, and western Nelson Counties, the New Rockford Dunes in central Eddy County, the Stanton Dunes in southeastern Mercer and southwestern McLean County, the Tappen Dunes in southeastern Kidder County, the Edinburg Dunes in north-central Walsh County, the Carson Dunes in northeastern Grant County, the Edson\Larimore Dunes in west-central Grand Forks County, the Hatton Dunes in northwestern Traill County, the Winona Flats and Linton Dunes in southwestern Emmons County and several additional areas (Figure 15) where dune deposits occur with areal extents less than ten square miles.

Fluvial Sands

The river channels and floodplains along North Dakota's major river systems (Figure 19) also contain significant deposits of sand (and gravel) that are commonly deposited within the river valley as well sorted channel sands and bar deposits (Figure 20).



Figure 19. View to the southeast of sand bar deposits in the Missouri River channel at south Bismarck. Seasonal variations in flow help to modify the location and extent of these types of deposits.

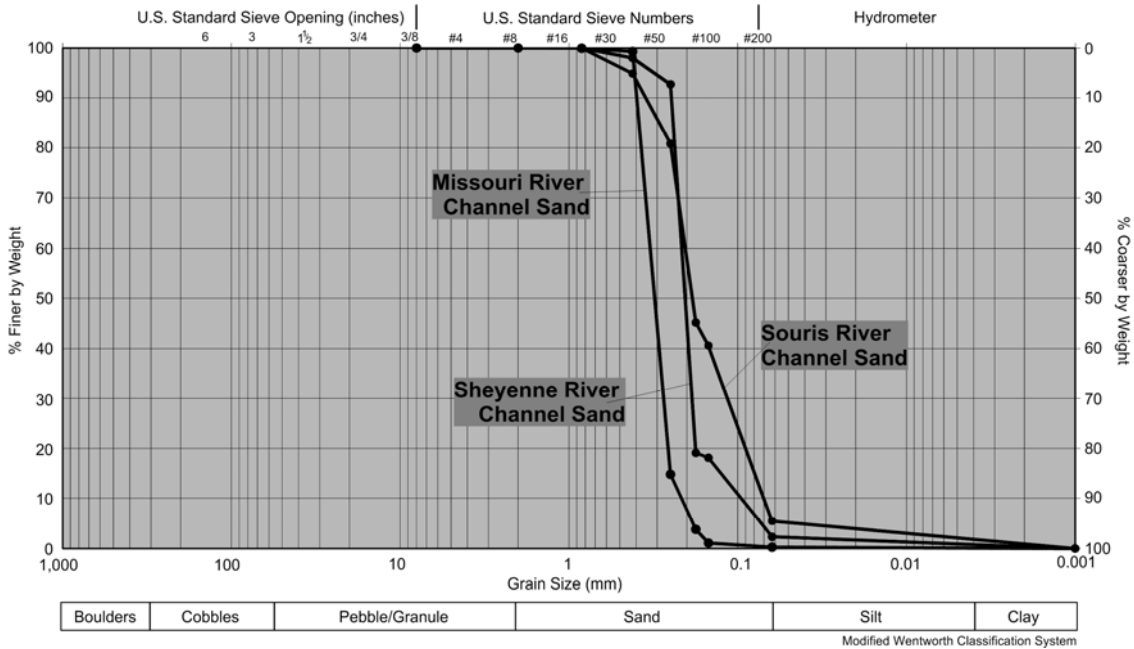


Figure 20. Field grain-size distribution curves of channel sands collected from the Missouri, Souris, and Sheyenne Rivers in North Dakota.



Figure 21. Bulk sample photomicrograph (25x) of fluvial channel sands of the Sheyenne River in Cass County near Horace in southeastern North Dakota.

With respect to sediment age and maturity, these types of deposits (Figure 19) can be considered to be some of the youngest, and consequently, less mature sediments, both from a mineralogic and textural (i.e. particle shape) standpoint. Carbonates, shales, and lignites are common components of these fluvial deposits (as well as others found across North Dakota) and can be problematic, depending upon the ultimate end use. The majority of these types of sand deposits are restricted to the Missouri, Souris, James, Sheyenne, and Red River Valleys (Plate I) and within other modern fluvial systems such as the Heart, Cannonball, Knife, Little Missouri, and others. Collectively, fluvial deposits (as described in this report) cover an area of 3,183 square miles (~2 million acres) and constitute the largest portion of the surficial sand and gravel resources mapped in the state.

SAMPLE COLLECTION METHODOLOGY

Description of Sample Collection

Samples of sand were obtained primarily from three different sources during this investigation: 1) sand samples were collected as submitted from individual private landowners who reported appreciable amounts of sand occurring on their particular properties of interest, 2) sand samples were obtained as submitted from various commercial sand and gravel producers in the state, and 3) sand samples of opportunity and of pertinent geological origin were also collected by the NDGS during the conduct of field work on various unrelated projects across the state and for the deliberate collection of selected samples of geologic interest. 125 individual sand samples were collected over the course of the investigation, with 105 being collected by the NDGS, along with 10 each from private landowners and sand and gravel producers in industry (Figure 1). From these samples, and based on available funding for testing and analysis, ten samples (four from N.D. private landowners, four from industry producers and two collected by the NDGS based on the geologic origin of the deposits), were selected. The selection of samples for further testing and characterization was based on several factors including: initial sand quality and character, location, and geological origin of the sampled deposits.

Samples Collected from Private Landowners

Private landowners from across North Dakota submitted sand samples collected from their respective properties of interest. These samples were considered as reconnaissance grab type samples and each was evaluated qualitatively, based on the sedimentary characteristics (sorting, grain shape, and mineralogy) of the sample. Candidate samples with favorable characteristics were chosen to have additional sample volume collected for further testing and characterization in accordance with current sand proppant testing specifications (Appendix I). Four samples were selected from this group (Table 4) and included: one sample collected from glaciofluvial sediment of the Coleharbor Formation (Qcrh) in southern Ward County (Sample No. 2), one sample collected from eolian sand of the Oahe Formation (Qtou) in central McHenry County (Sample No. 3), one sample collected from Quaternary and Tertiary (undivided) age sediments dominantly of fluvial origin (QTu) in northeastern McKenzie County (Sample No. 4), and one sample collected from Pleistocene age glacial sediments (Qcdn) in northwestern McKenzie County (Sample No. 9).

Samples Obtained from Industry Producers

Several sand and gravel producers (Abrasives, Inc., Northern Improvement, and Strata Corporation) currently operating in North Dakota also submitted samples from their respective deposits of interest. These samples were also considered initially as reconnaissance grab type samples and each was also evaluated qualitatively, based on the sedimentary characteristics of the sample. Candidate samples with favorable characteristics, in addition to other factors such as deposit location, were chosen for additional sample collection and submittal for further testing and characterization in accordance with current sand proppant testing specifications (Appendix I).

Table 4. Selected Sand Samples Location and Description Summary.

No.	County	Location (T., R., Sec.)	Geologic Map Unit	Longitude	Latitude	Geologic Map Unit Description
1	McHenry	156-77-6	Qod	-100.61	48.36	Windblown Sand (Holocene)-Well-sorted, medium sand with obscure bedding; poorly developed paleosols common; as thick as 30 feet (10 meters); knobby topography consisting of inactive transverse or longitudinal dunes nearly obliterated by more recent blowouts.
2	Ward	151-84-33	Qcrh	-101.43	47.85	Collapsed river sediment-(Holocene to Pre-Wisconsinan)-Moderately well-sorted, cross-bedded sand and plane-bedded gravel, including sediment of melt-water and other rivers; as thick as 100 feet, faulted and contorted supraglacial sediment with hummocky topography.
3	McHenry	158-75-28	Qtou	-100.35	48.47	Sand of the Oahe and older Formations, undivided (Holocene to Pliocene)-windblown sand of the Oahe Formation, as thick as 10 feet, and sand of older formations with an undulating wind-scoured surface.
4	McKenzie	150-99-1	QTu	-103.29	47.84	Quaternary and upper Tertiary sediment, undivided-largely river sediment; includes upper Quaternary terrace, fan, and pediment derived material such as sandstone, silicified wood, and concretions and Pliocene(?) to middle(?) Quaternary clay, silt, sand, and gravel composed of rounded pebbles and cobbles of quartzite and porphyry derived from the Black Hills or Rocky Mountains; as thick as 300 feet.
5	Grant	134-88-31	Tb	-101.78	46.37	Bullion Creek Formation (Paleocene) - Yellow-brown silt, sand, clay, sandstone, and lignite; river, lake and swamp sediment as thick as 600 feet.
6	Burleigh	142-77-10	Tb	-100.42	47.13	Bullion Creek Formation (Paleocene) - Yellow-brown silt, sand, clay, sandstone, and lignite; river, lake and swamp sediment as thick as 600 feet.
7	McHenry	154-78-29	Qcrf	-100.72	48.13	Uncollapsed river sediment-flat-bedded sediment of gently sloping plains and terraces, commonly with braided-channel scars.
8	Grand Forks	150-52-29	Qcew	-97.33	47.78	Wave-Eroded glacial sediment-glacial sediment with flat to gently undulating topography resulting from wave erosion; covered by a thin gravel lag in places.
9	McKenzie	151-102-35	Qcdn	-103.70	47.85	Draped Glacial Sediment-Thin glacial sediment draped over and only slightly modifying the non-glacial topography existing before the last glacial advance.
10	Burleigh	137-77-30	Tc	-100.44	46.65	Cannonball Formation (Paleocene)-Olive-brown sand, shale, and sandstone; marine shoreline and offshore sediment; as thick as 400 feet.

Geologic Map Unit Descriptions from the Geologic Map of North Dakota (Clayton et. al. 1980)

Four samples were selected from this group (Table 4) and included: one sample from bedrock sediments of Tertiary age from the Bullion Creek Formation (Tb) in west-central Grant County (Sample No. 5), one sample from a sandstone outcrop of the Bullion Creek Formation (Tb) in northern Burleigh County (Sample No. 6), one sample from glaciofluvial sands of the Coleharbor Formation (Qcrf) in southwestern McHenry County (Sample No. 7), and one sample from glaciolacustrine sediments of the Coleharbor Formation (Qcew) in southeastern Grand Forks County (Sample No. 8).

Samples Collected based on Geological Origin

Samples were also collected by the NDGS based on their sedimentary characteristics resultant from their geologic origin. Samples from surficial, unconsolidated deposits in alluvial, glaciofluvial and glaciolacustrine, eolian, and in exposed consolidated sedimentary bedrock settings, were collected and evaluated qualitatively based on the sedimentary characteristics of the sample. Candidate samples with favorable sedimentological characteristics, in addition to other factors such as deposit location and uniqueness of geologic setting, were chosen for additional sample collection and characterization in accordance with current sand proppant testing specifications (Appendix I). Two samples were selected (Table 4) from this group. One sample of Holocene age eolian sand of the Oahe Formation from the Denbigh Dunes (Qod) area in north-central McHenry County (Sample No. 1), and one sample of Tertiary age from bedrock sediments of the Cannonball Formation (Tc) in southern Burleigh County (Sample No. 10) were chosen.

DESCRIPTION OF TESTING AND RESULTS

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

Sample Preparation

All samples submitted for testing were properly prepared for analysis by washing, drying, and disassociation. A percentage of the material removed during sample preparation constitutes the individual samples mass loss (commonly fines) and may be representative of the initial amount of material that can be expected to be removed (or lost) during the bulk volume washing process during production. The sample with the lowest reported fines lost was Sample No. 8 at 4.1%, and the sample with the highest reported fines lost was Sample No. 1 at 30%. The average loss was 9.3% for all of the samples tested (Table 5).

Particle Size Distribution – Textural (Sieve) Analysis

Sieve analyses are conducted on sediment samples in order to characterize the amounts of different sized sand grains within an individual sample. A series of stacked, wire-mesh sieves of standard sizes, are used to sieve each sand sample. Amounts of sands either being retained by the screen on each successively smaller opening sized sieve (% retained) or passing through the screen (% passing) is recorded and reported commonly as tabular data (Table 6) or in graphical form on a grain-size distribution diagram (Figure 22).

The resulting graph and grain-size curve conveys information on the amounts of particle sizes present and the degree of sorting or the variability (or lack thereof) of grains sizes. A well sorted sample (poorly graded in engineering parlance), will have much of the sample volume within or near the same or similar size classes (Table 7), resulting in a very steep curve on the grain size distribution diagram (Figure 23). All of the samples selected for testing were well sorted (poorly graded) sands. Conversely, a poorly sorted sample will have small amounts of grains of many different sizes which will result in a grain-size distribution diagram with a more gradual curve.

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

Table 5. Calculated % Fines Loss on Sample Preparatory Wash.

No.	Sample ID	Initial Weight (g)	Weight after Wash (g)	Weight Loss (g)	Loss (%)	Geologic Unit
1	NDGS-GO-DD	11422.46	7994.24	3428.2	30.0	Qod
2	NDGS-PL-BH	13925.93	12202.22	1723.7	12.4	Qcrh
3	NDGS-PL-JN	14258.92	13559.52	699.4	4.9	Qtou
4	NDGS-PL-JD	14689.88	13594.58	1095.3	7.5	Qtu
5	NDGS-IP-AI	19788.61	18496.88	1291.7	6.5	Tb
6	NDGS-IP-NI	16724.49	14991.34	1733.2	10.4	Tb
7	NDGS-IP-SC	26659.81	24676.96	1982.9	7.4	Qcrf
8	NDGS-IP-SC	20797.46	19949.45	848.01	4.1	Qcew
9	NDGS-PL-EB	16075.19	15192.66	882.53	5.5	Qcdn
10	NDGS-GO-TC	16360.04	15697.41	662.63	4.1	Tc

GO: Geologic Origin, PL: Private Landowner, IP: Industry Producer

Table 6. Bulk Composite Sample Sieve Analysis Results (Weight Percent Retained).

Sample No. U.S. Standard Sieve No.	1 NDGS-GO-DD	2 NDGS-PL-BH	3 NDGS-PL-JN	4 NDGS-PL-JD	5 NDGS-IP-AI	6 NDGS-IP-NI	7 NDGS-IP-SC	8 NDGS-IP-SC	9 NDGS-PL-EB	10 NDGS-GO-TC
6	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	6.7	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0
12	0.0	0.4	0.0	0.1	0.0	0.0	5.4	18.1	0.0	0.0
14	0.0	0.2	0.0	0.6	1.1	0.0	6.9	4.7	0.0	0.0
16	0.0	0.3	0.0	0.1	4.6	0.0	7.0	4.7	0.0	0.0
18	0.0	0.5	0.1	0.3	11.6	0.0	7.5	5.1	0.0	0.0
20	0.0	0.7	0.4	0.3	17.6	0.1	7.8	5.2	0.0	0.0
25	0.0	1.1	1.6	0.6	24.7	0.2	9.5	5.7	0.0	0.0
30	0.1	1.6	4.0	1.2	21.6	0.4	8.9	5.7	0.1	0.0
35	0.1	2.1	7.6	2.2	7.5	0.8	7.9	5.7	0.1	0.0
40	0.1	2.6	9.8	3.3	3.4	1.2	5.6	5.9	0.5	1.1
45	0.2	5.1	12.7	7.3	3.4	2.3	6.3	7.9	3.0	0.3
50	0.3	6.8	12.6	10.4	2.0	3.4	5.0	8.6	8.5	1.1
60	1.2	8.2	11.1	13.1	1.3	6.0	4.3	8.1	13.9	5.0
70	4.6	10.5	10.5	17.8	0.7	13.7	2.1	7.1	20.0	9.7
80	8.5	11.5	8.4	17.4	0.3	20.9	1.6	4.2	18.7	16.7
100	14.1	14.1	8.2	14.3	0.0	24.4	1.4	2.1	15.8	27.9
120	18.1	12.5	6.0	7.0	0.0	13.9	0.9	0.6	8.9	24.8
140	20.4	11.7	4.4	2.8	0.0	7.8	0.1	0.4	5.3	8.6
170	13.4	6.6	1.9	0.9	0.0	3.2	0.3	0.2	2.8	2.5
200	10.7	3.4	0.6	0.5	0.0	1.8	0.1	0.1	1.9	1.8
230	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
270	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
325	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pan	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

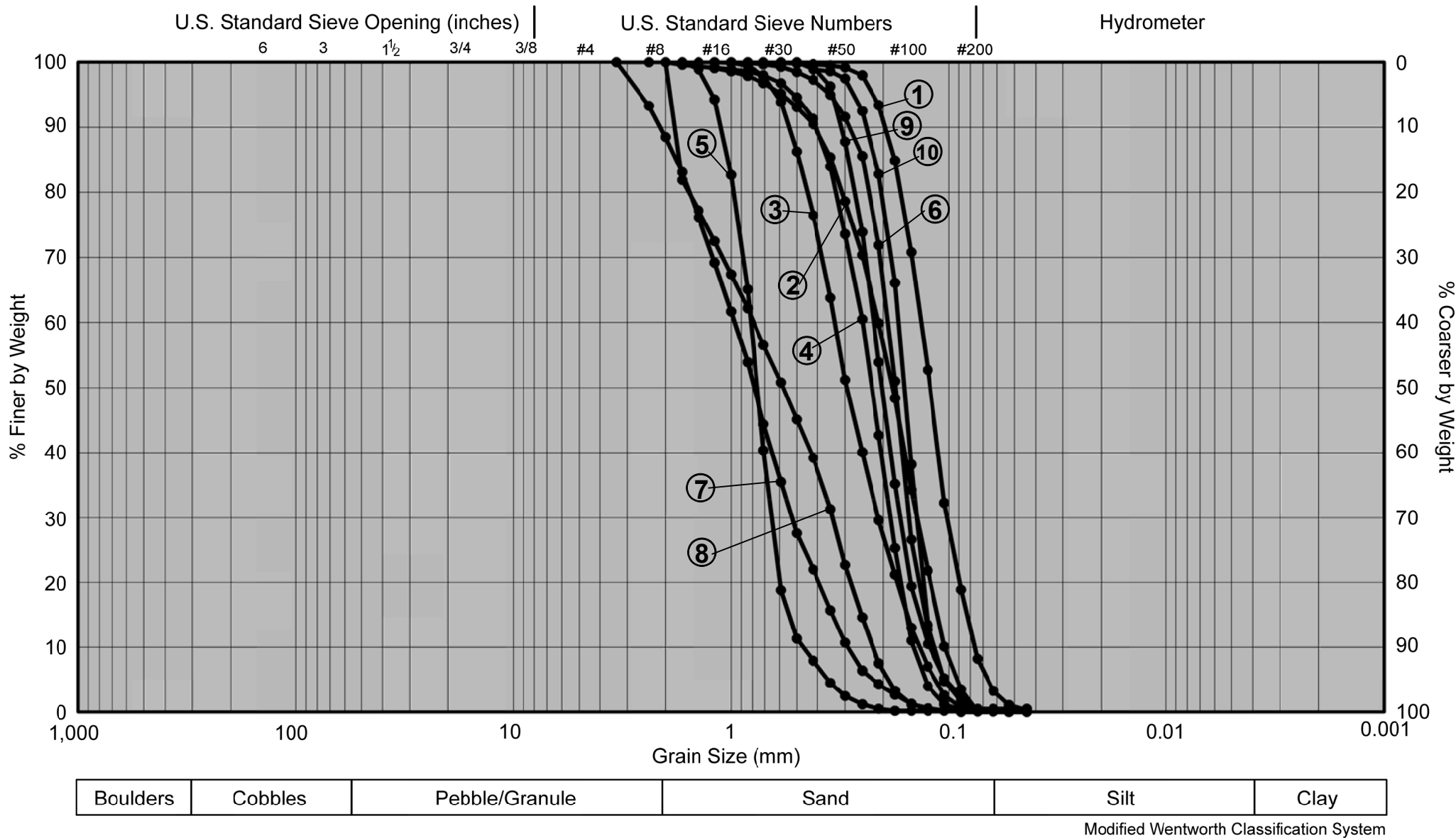


Figure 22. Bulk sample grain-size distribution curves for selected sand samples from North Dakota: Sample No. 1 - Windblown Sand (Qod) from the Denbigh Dunes area in McHenry County, Sample No. 2 - Glaciofluvial sand (Qcrh) from northern McLean County, Sample No. 3 - Windblown Sand (Qtou) of the Denbigh Dunes area in northeastern McHenry County, Sample No. 4 - Fluvial sand (QTu) from north-central McKenzie County, Sample No. 5 - Fluvial Sand (pre-processed) from bedrock sediments (Tb) in northwestern Grant County, Sample No. 6 - Fluvial sand (Tb) from bedrock sediments in north-central Burleigh County, Sample No. 7 - Glaciofluvial sands (Qcrf) from southwestern McHenry County, Sample No. 8 - Glaciolacustrine (Qcdn) sands from southwestern Grand Forks County, Sample No. 9 - Glacial drift sands (Qcdn) from west-central McKenzie County, Sample No. 10 - Fluvial sand (Tc) from bedrock sediments of the Cannonball Formation in southern Burleigh County.

Table 7. Selected Most Abundant Sized Sample Sieve Analysis Results (Weight Percent Retained).

Sample No.	1	2	3	4	5	6	7	8	9	10
U.S. Standard Sieve No.	40/70	30/50	30/50	30/50	30/50	30/50	30/50	30/50	30/50	40/70
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.8	1.2	0.2	3.8	0.1	2.4	2.0	0.2	0.0
35	0.0	10.8	20.0	9.1	34.2	9.0	26.2	19.5	0.8	0.0
40	0.0	16.1	24.5	15.0	26.0	16.6	24.3	199.0	13.8	0.0
45	0.0	30.2	30.3	30.8	22.8	26.7	26.9	27.8	29.8	0.0
50	0.2	40.8	23.6	44.5	13.2	41.3	20.2	30.0	55.1	3.3
60	20.1	1.3	0.5	0.4	0.1	6.2	0.0	0.8	0.2	29.9
70	75.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	60.6
80	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2
100	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pan	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Total	99.9	100.0	100.1	100.0	100.1	100.0	100.0	279.1	100.0	100.0
In-Size	95.8	97.9	98.3	99.3	96.2	93.6	97.6	97.2	99.5	93.8

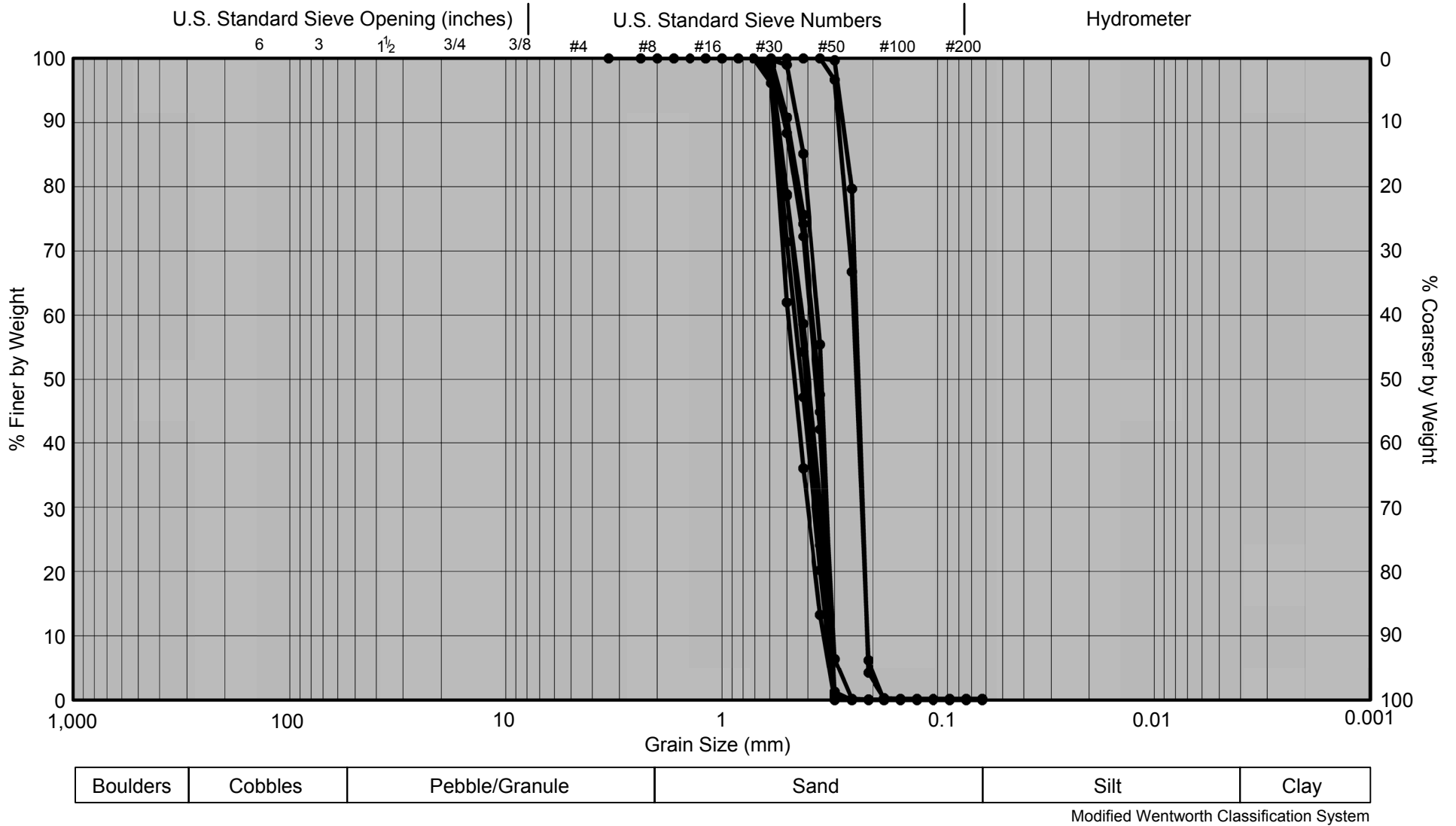


Figure 23. Grain size distribution curves for selected sands sized for testing and characterization as natural sand proppant.

All of the samples selected for further testing and characterization as potential proppants fall into the grain size ranges for classification as a “Sand” according to the Modified Wentworth classification scheme (Figure 22) and can be further characterized as well sorted (poorly graded) to very well sorted, fine to medium grained sands. Five samples (Sample Nos. 1, 2, 6, 9, and 10) had their most abundant amount in the 70/140 size range, three samples (Sample Nos. 3, 4, and 8) had their most abundant sand size amount in the 40/70 size range, with the remaining two samples (Sample Nos. 5 and 7) tested having their most abundant amounts in the 16/30 size range (Table 8).

Additional engineering statistical analyses can also be completed on data generated in a grain-size distribution diagram, which can be used to quantitatively compare individual samples for potential engineering applications. The mean grain-size diameter is commonly used to characterize proppant distribution in hydraulic fracturing applications and the median grain-size diameter is used to characterize gravel-packing distributions (Table 9).

% Clusters

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

Sample Nos. 1, 6, 7, and 8 each had sand grain clusters reported at approximately 1% by visual-manual microscopic inspection methods. Sample Nos. 2-5, 9 and 10 reported no sand grain clusters observed (Table 2) in the field of count (NIFC).

Sand Grain Morphology (Sphericity and Roundness)

Individual sand grain sphericity and roundness are two shape factors that are evaluated when characterizing a sand for potential use as a proppant and can be qualitatively observed through standard photomicrographs (Figure 24). Sphericity refers to how closely a particular grain of sand resembles that of a sphere and roundness refers to the shapes of the corners of an individual sand grain. A sand with high sphericity and roundness is desirable. Recommended sphericity and roundness values of 0.6 or greater are desirable for frac sand, with values of 0.7 or greater for proppants characterized as being of high-strength (API, 1995a and b).

All samples tested had sphericity values reported at 0.6 or greater (Table 2). Sample No. 2, consisted of collapsed fluvial sands of the Coleharbor Formation in northeastern McLean County and had a reported sphericity value of 0.7. Roundness values of 0.5 were reported for samples 1, 3, 9, and 10 which are just under the recommended values of 0.6 for natural sands. Samples 2, and 4-8, reported roundness values of 0.6 (Figure 25).

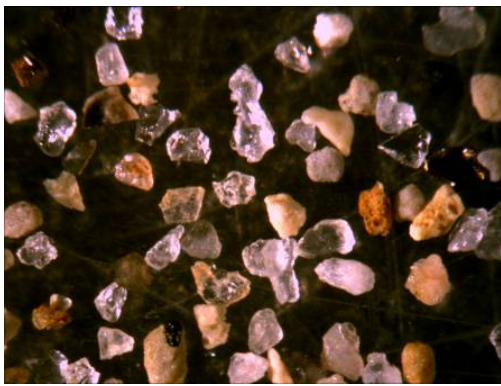
Table 8. Bulk Composite Sample Sieve Analysis Results (Percent In-Size).

Sample No.\ID Size Class	1 NDGS-GO-DD	2 NDGS-PL-BH	3 NDGS-PL-JN	4 NDGS-PL-JD	5 NDGS-IP-AI	6 NDGS-IP-NI	7 NDGS-IP-SC	8 NDGS-IP-SC	9 NDGS-PL-EB	10 NDGS-GO-TC
6/12	0.0	0.4	0.0	0.1	0.0	0.0	16.8	18.1	0.0	0.0
8/16	0.0	0.9	0.0	0.7	5.8	0.0	24.1	27.5	0.0	0.0
12/20	0.1	1.8	0.6	1.3	35.0	0.1	29.1	19.7	0.0	0.0
16/30	0.1	4.0	6.2	2.4	75.5	0.6	33.6	21.7	0.1	0.0
20/40	0.2	7.5	23.1	7.3	57.2	2.6	31.9	22.9	0.6	1.1
30/50	0.6	16.6	42.7	23.1	16.4	7.7	24.8	28.1	12.1	2.4
40/70	6.2	30.6	46.8	48.6	7.5	25.4	17.7	31.8	45.4	16.1
70/140	61.0	49.7	27.0	41.4	0.4	67.0	4.0	7.2	48.7	78.0

Table 9. Grain-Size Distribution Engineering Statistics Summary.

Sample No.	Sample Type	ISO Mean Particle Dia. (mm)	Median Particle Dia. d_{50} (mm)	Graphical d_{90} (mm)	Graphical d_{84} (mm)	Standard Deviation ¹	Geologic Unit
1	Composite	0.135	0.134	0.19	0.17	1.27	Qod
	40/70	0.239	0.236	0.28	0.18	0.76	
2	Composite	0.245	0.201	0.42	0.32	1.59	Qcrh
	30/50	0.394	0.386	0.51	0.48	1.24	
3	Composite	0.268	0.283	0.55	0.48	1.70	Qtou
	30/50	0.428	0.418	0.53	0.51	1.22	
4	Composite	0.268	0.239	0.32	0.30	1.26	Qtu
	30/50	0.388	0.380	0.50	0.46	1.21	
5	Composite	0.779	0.739	1.10	1.00	1.35	Tb
	30/50	0.465	0.455	0.48	0.43	0.95	
6	Composite	0.197	0.182	0.27	0.23	1.26	Tb
	30/50	0.383	0.374	0.50	0.46	1.23	
7	Composite	1.004	0.779	2.10	1.80	2.31	Qcrf
	30/50	0.443	0.433	0.57	0.53	1.22	
8	Composite	0.818	0.614	1.85	1.80	2.93	Qcew
	30/50	0.421	0.411	0.54	0.51	1.24	
9	Composite	0.213	0.199	0.31	0.29	1.46	Qcdn
	30/50	0.367	0.362	0.43	0.41	1.13	
10	Composite	0.174	0.165	0.22	0.21	1.27	Tc
	40/70	0.245	0.243	0.28	0.27	1.11	

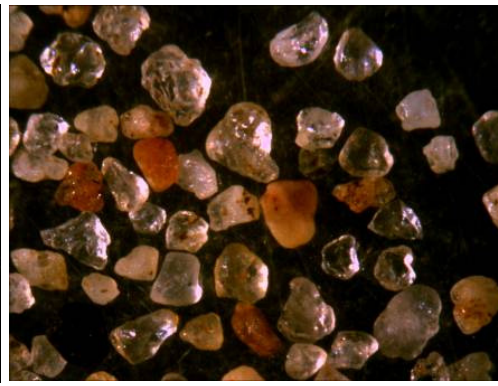
¹ Standard Deviation calculated as d_{84}/d_{50}



Sample No. 1 Qod 40/70



Sample No. 2 Qcrh 30/50



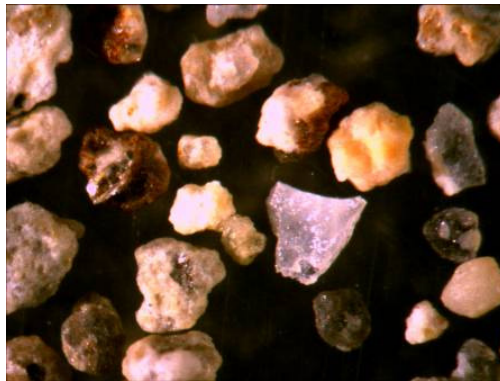
Sample No. 3 Qtou 30/50



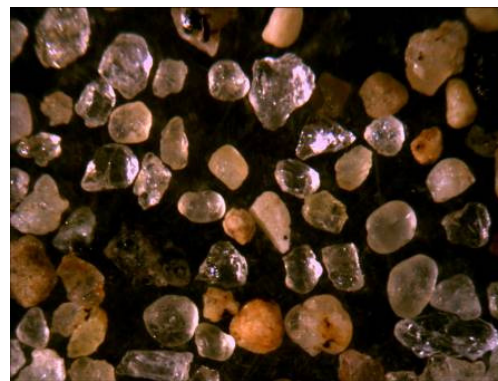
Sample No. 4 Qtu 30/50



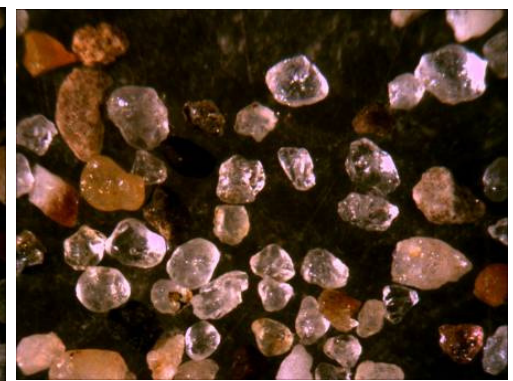
Sample No. 5 Tb 30/50



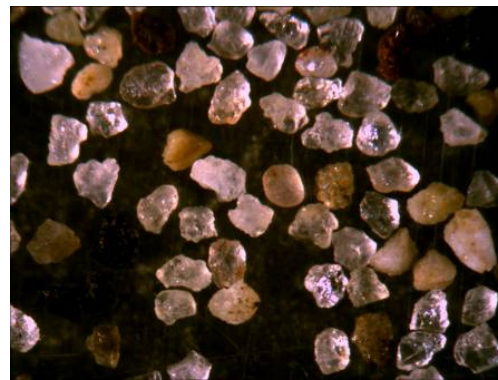
Sample No. 6 Tb 30/50



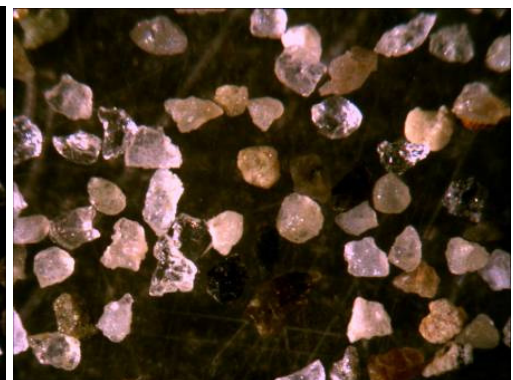
Sample No. 7 Qcrf 30/50



Sample No. 8 Qcew 30/50



Sample No. 9 Qcdn 30/50



Sample No. 10 Tc 40/70

Figure 24. Standard (40x) photomicrographs of individual selected sand samples in North Dakota tested for use as proppants for hydraulic fracturing of oil & gas wells.

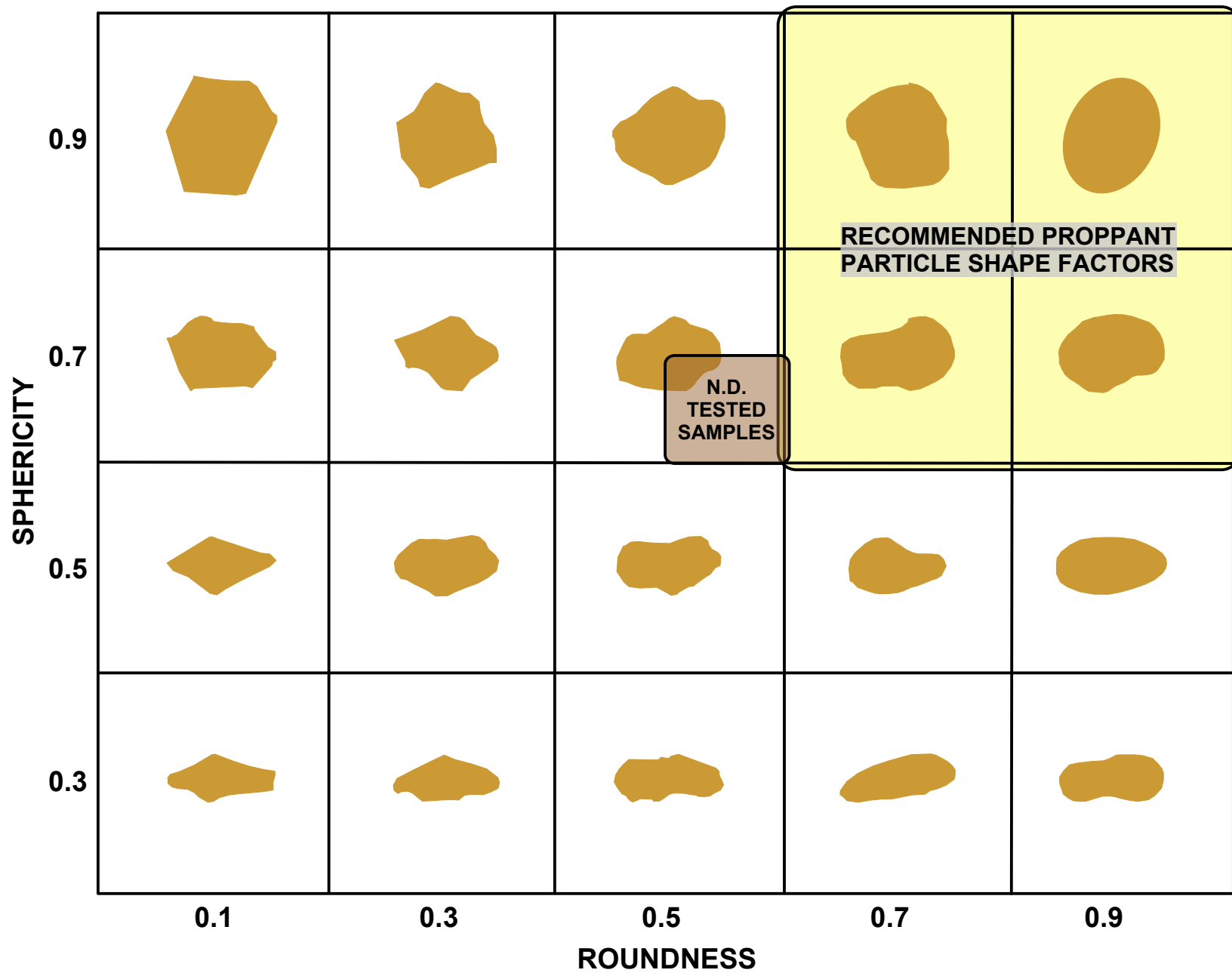


Figure 25. Sphericity and roundness chart displaying the range of recommended proppant particle shape factors and range of values for sand samples tested from sand deposits in North Dakota.

Acid Solubility

The amount of particular sand that is soluble in a strong acid is an important characteristic of an effective proppant as acid treatments of oil and gas wells during completions are common in the hydraulic fracturing industry. API (1995a) recommends no greater than 2% (by weight) of 30/50 or larger sized sand and no greater than 3% (by weight) of 40/70 or smaller sized sand, to be used as proppant be soluble in a 12:3 hydrochloric (HCL) to hydrofluoric (HF) acid solution. None of the samples tested were below the recommended acid solubility of 2% and 3% or less (Figure 26). Acid solubility on tested sands ranged from 5.9% from a sample collected from the Bullion Creek Formation in west-central Grant County to a very high value of 56.8% in a sample collected from a well-cemented outcrop of Bullion Creek Formation sandstone in northwestern Burleigh County.

Silt and Clay Fines Testing (Turbidity)

Turbidity measures an optical property of a water sample with a particular amount of suspended sediment contained within it. It is commonly used to determine the percentage amount of fine materials (e.g. silts and clays) that may be present within a particular sample. With respect to a sand sample to be used as potential proppant, turbidity is a method to measure the amount of associated fines contained within a particular sand sample. It can be used to determine what sand sources may need additional preparatory steps (e.g. washing) during initial processing of the raw mined product into an eventual final frac-sand product. Turbidity is measured and commonly reported in Formazin Turbidity Units (FTU), which are standard suspensions where turbidity values are determined and reported against. The recommended limit of tested frac sand would be less than 250 FTU. All the samples tested for characterization for use as natural proppants were well below the recommended limit of 250 FTU and ranged from 8 FTU in sands collected from glacially derived collapsed river sediment of the Coleharbor Formation in northwestern McLean county to 36 FTU from sand collected from a well-cemented sandstone outcrop of the Tertiary Bullion Creek Formation in northwestern Burleigh County (Figure 27).

Crush Resistance

Since the composition of sands can be quite variable (remembering that sand is in fact a size term that does not reflect the compositional or mineralogical character of a particular sample), the resultant strengths of sands are also highly variable. The measuring of the amount of fine-grained material generated during the subsection of a given sand sample (within a specified size range) to a pre-determined amount of stress or load is done by a crush resistance test. Crush resistance testing was performed on all ten of the selected samples that were submitted for testing and characterization as proppant for use in the hydraulic fracturing of oil and gas wells (Figure 28). Samples were subjected to one set of three predetermined stresses, depending on the size range of the tested samples, and a resultant K-value was determined. A K-value is determined from the amount of crushed fines generated at a particular applied stress value and is defined as the highest stress level that will generate no more than 10% crushed material (rounded down to the nearest 1,000 psi).

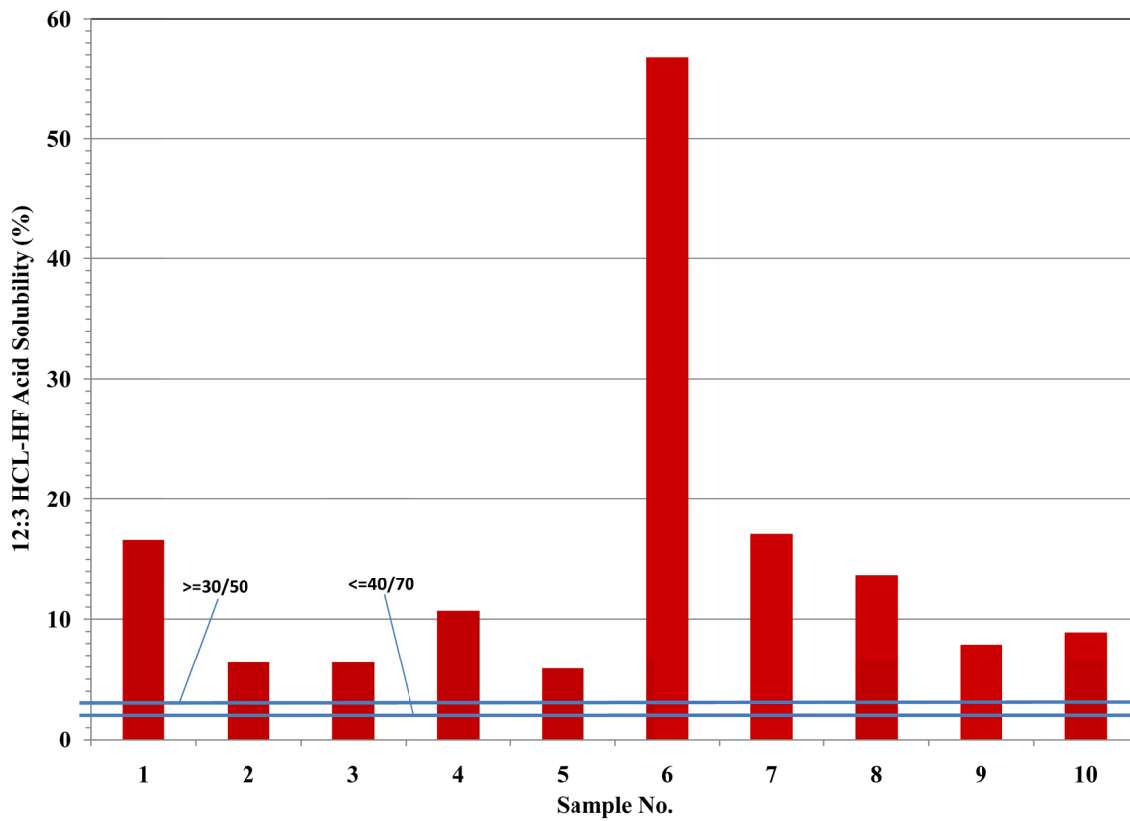


Figure 26. Comparison of HCL:HF Acid solubility results for sand samples tested for use as proppants.

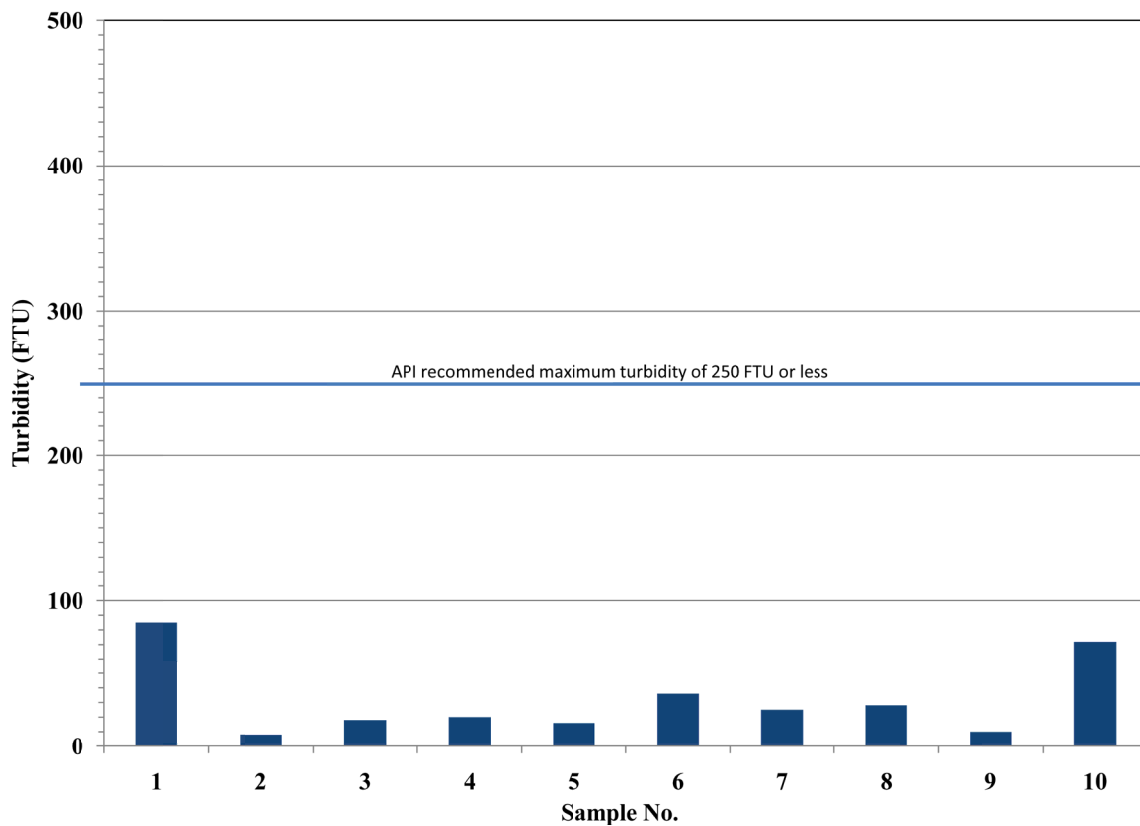


Figure 27. Comparison of turbidity results for sand samples tested for use as proppants.

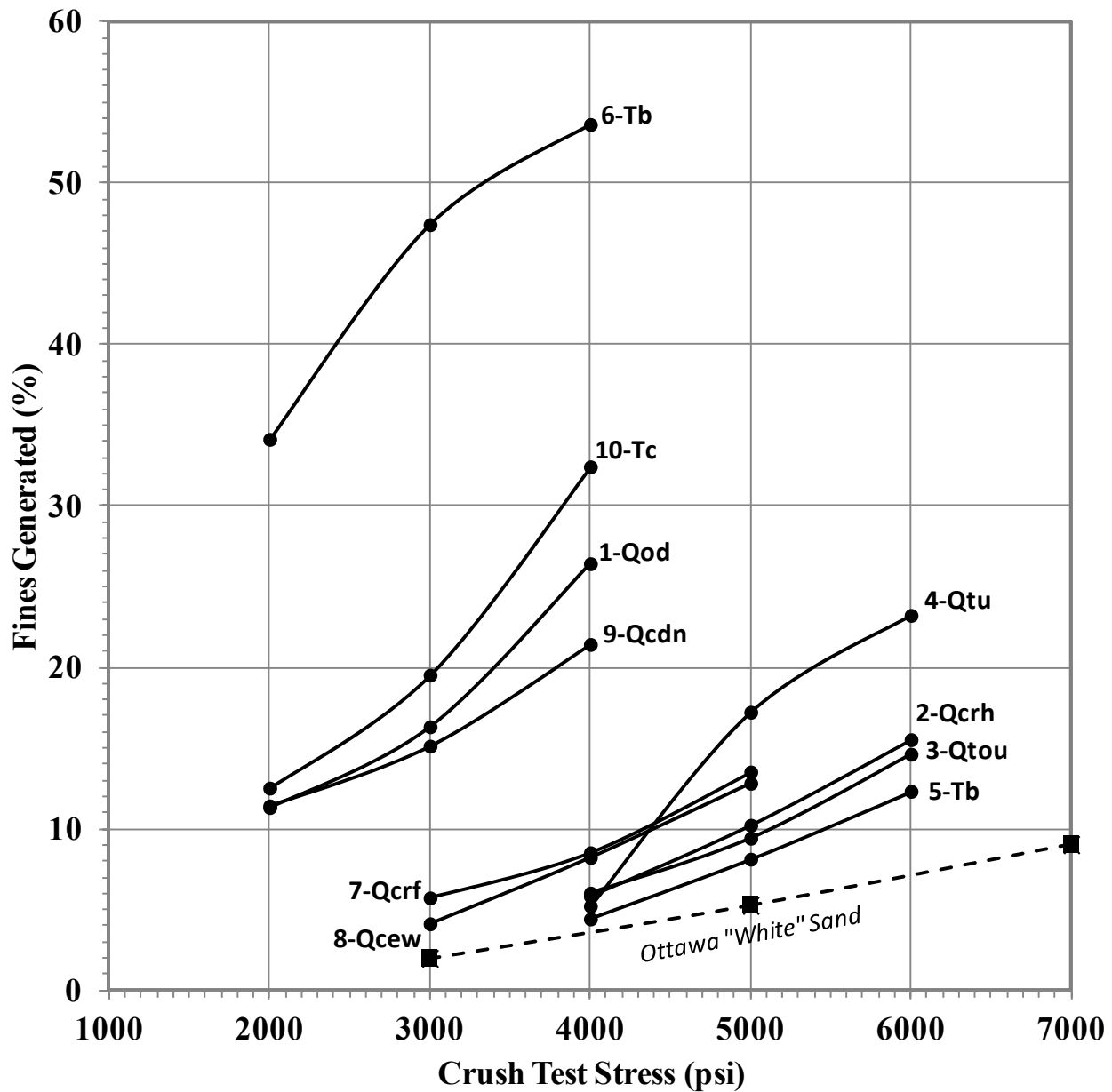


Figure 28. Bulk sample grain-size distribution curves for selected sand samples from North Dakota: Sample No. 1 - Windblown Sand (Qod) from the Denbigh Dunes area in McHenry County, Sample No. 2 - Glaciofluvial sand (Qcrh) from northern McLean County, Sample No. 3 - Windblown Sand (Qtou) of the Denbigh Dunes area in northeastern McHenry County, Sample No. 4 - Fluvial sand (QTu) from north-central McKenzie County, Sample No. 5 - Fluvial Sand (pre-processed) from bedrock sediments (Tb) in northwestern Grant County, Sample No. 6 - Fluvial sand (Tb) from bedrock sediments in north-central Burleigh County, Sample No. 7 - Glaciofluvial sands (Qcrf) from southwestern McHenry County, Sample No. 8 - Glaciolacustrine (Qcdn) sands from southwestern Grand Forks County, Sample No. 9 - Glacial drift sands (Qcdn) from west-central McKenzie County, Sample No. 10 - Fluvial sand (Tc) from bedrock sediments of the Cannonball Formation in southern Burleigh County.

Sample Nos. 1, 6, 9, and 10 were subjected to a stress level set of 2,000, 3,000, and 4,000 psi and generated K-values of <2K. Sample Nos. 7 and 8 were subjected to a three stress level set of 3,000, 4,000, and 5,000 psi and generated K-values of 4K. Sample Nos. 2, 3, 4, and 5 were subjected to a stress level set of 4,000, 5,000, and 6,000 psi and generated K-values of 4K, 5K, 2K, and 5K, respectively (Table 10). Representative Ottawa “white” sands commonly generate K-values around 7K. It appears that the selected sands tested could find use in the hydraulic fracturing of oil and gas wells in reservoir applications where the fracture closure stresses are less than 5,000 psi.

Mineralogy (X-Ray Diffraction)

Bulk sample geochemistry was analyzed through X-Ray Diffraction (XRD) on five of the ten samples submitted for testing for use as proppants (Table 11). XRD analysis is commonly used to determine the mineralogy of fine-grained sediments, particularly clays (Poppe et. al. 2001). Generally, the five samples analyzed had similar overall mineralogical compositions with some variability within the lower percentages of contained carbonates and clays (Figure 29).

Sample No. 1, collected from the one of the larger dunes in the Denbigh Dunes area consisted of 85% silicates, 14% clays and carbonates, and 1% iron in the form of pyrite and other iron oxides. Sample No. 5, a processed sand sample collected from sands of the Bullion Creek Formation consisted of 98% silicates, with 1% each clays and carbonates and no reported iron minerals. Sample No. 7 collected from glaciofluvial sands of the Coleharbor Formation in McHenry County consisted of 81% silicates with 19% total clays and carbonates with no reported iron minerals. Sample No. 8, collected from sand and gravel lag deposits occurring on wave eroded glacial sediments on the margins of the former Glacial Lake Aggasiz consisted of 85% silicates with a combined total of 15% carbonates and clays and trace amounts of iron minerals. Sample No. 10, collected from sands of the Cannonball Formation in southern Burleigh County consisted of 84% silicates and a combined total of 15% clays and carbonates with 1% reported iron minerals in the form of iron oxides.

The marked difference between the higher silicates level in sample No. 5 of 98% as compared to the average value of 84% silicates for the remainder of the samples analyzed (Figure 29) could be reflective of the differences between a processed sand (i.e. sized, washed, etc.) and a raw sample that is reflective of the composite mineralogy of the deposit, where the samples originated, and may give some indication of the potential for increases in quality between a raw “pit-run” type material and a “refined” processed product. In comparison, Ottawa “white” silica sands are commonly 99% quartz sand.

Table 10. Crush Resistance Testing Summary.

Sample No.	1-Qod	2-Qcrh	3-Qtou	4-QTu	5-Tb	6-Tb	7-Qcrf	8-Qcew	9-Qcdn	10-Tc
Tested Stress (psi)	% Fines Generated on Crush									
2,000	11.3	--	--	--	--	34.1	--	--	11.4	12.5
3,000	16.3	--	--	--	--	47.4	5.7	4.1	15.1	19.5
4,000	26.4	5.8	6.0	5.2	4.4	53.6	8.5	8.2	21.4	32.4
5,000	--	10.2	9.4	17.2	8.1	--	13.5	12.8	--	--
6,000	--	15.5	14.6	23.2	12.3	--	--	--	--	--
K-Value	<2K	4K	5K	2K	5K	<2K	4K	4K	<2K	<2K

Table 11. Detailed X-Ray Diffraction Mineralogy Analyses on Selected Samples (Clay and Bulk).

Sample No.	Quartz (%)	Plagioclase (%)	K-Feldspar (%)	Calcite (%)	Dolomite (%)	Hornblende (%)	Micas (%)	Iron Oxides (%)	Pyrite (%)	Zeolites (%)	Total Clays (%)	Illite (%)	Smectite (%)	Chlorite (%)	Kaolinite (%)	Geologic Unit
1	57	15	12	2	4	1	--	--	1	--	8	3	5	tr.	tr.	Qod
5	68	10	20	1	--	--	--	--	--	--		tr.	1	tr.	tr.	Tb
7	53	14	12	6	10	2	--	--	--	--	3	1	2	tr.	tr.	Qcrf
8	45	19	19	3	10	2	--	--	tr.	--	2	1	1	tr.	tr.	Qcew
10	55	15	11	1	--	tr.	3	1	--	tr.	14	6	7	1	tr.	Tc

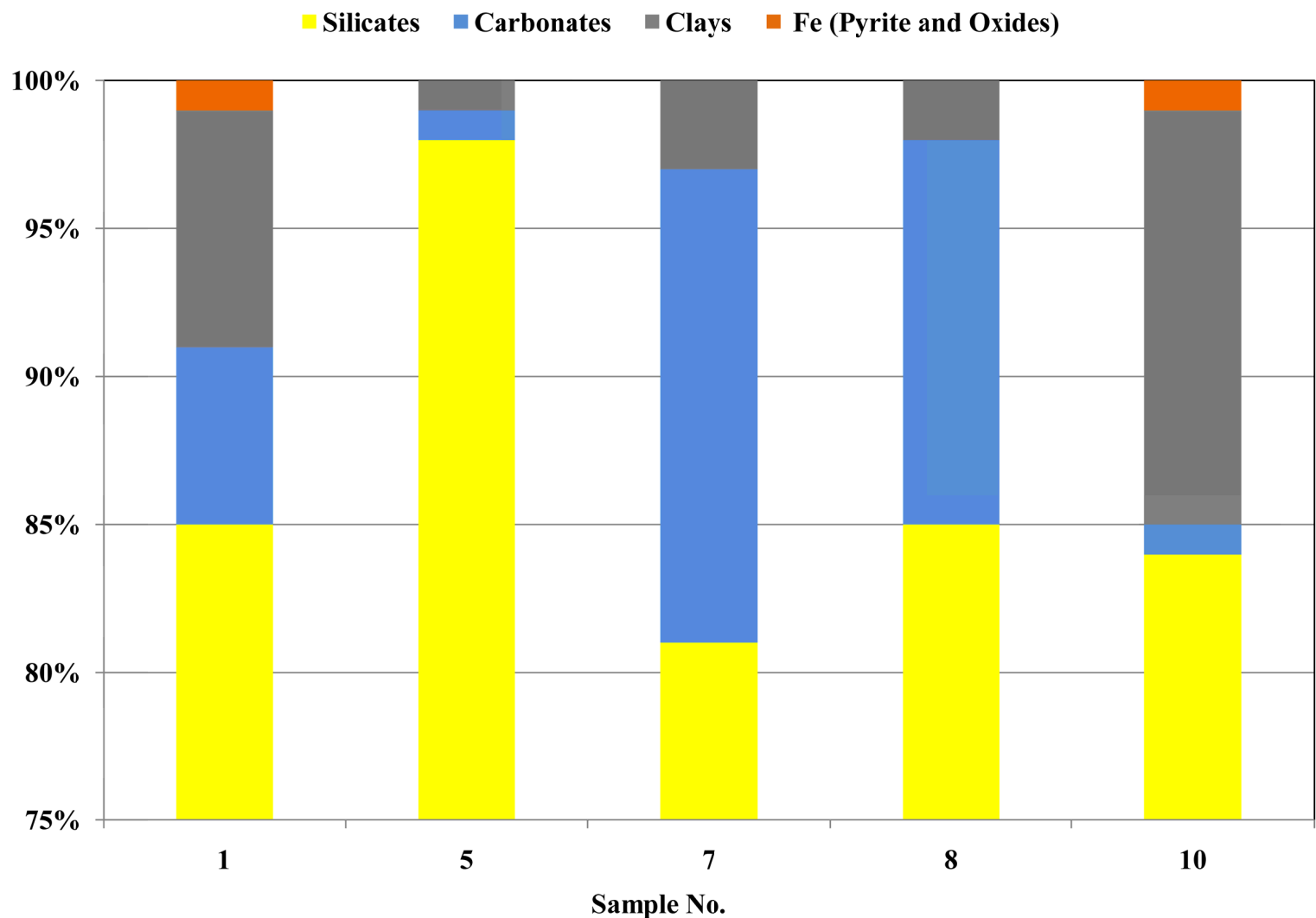


Figure 29. Bulk mineralogical compositional summary of selected sand samples in North Dakota as determined from X-Ray Diffraction (XRD) analyses.

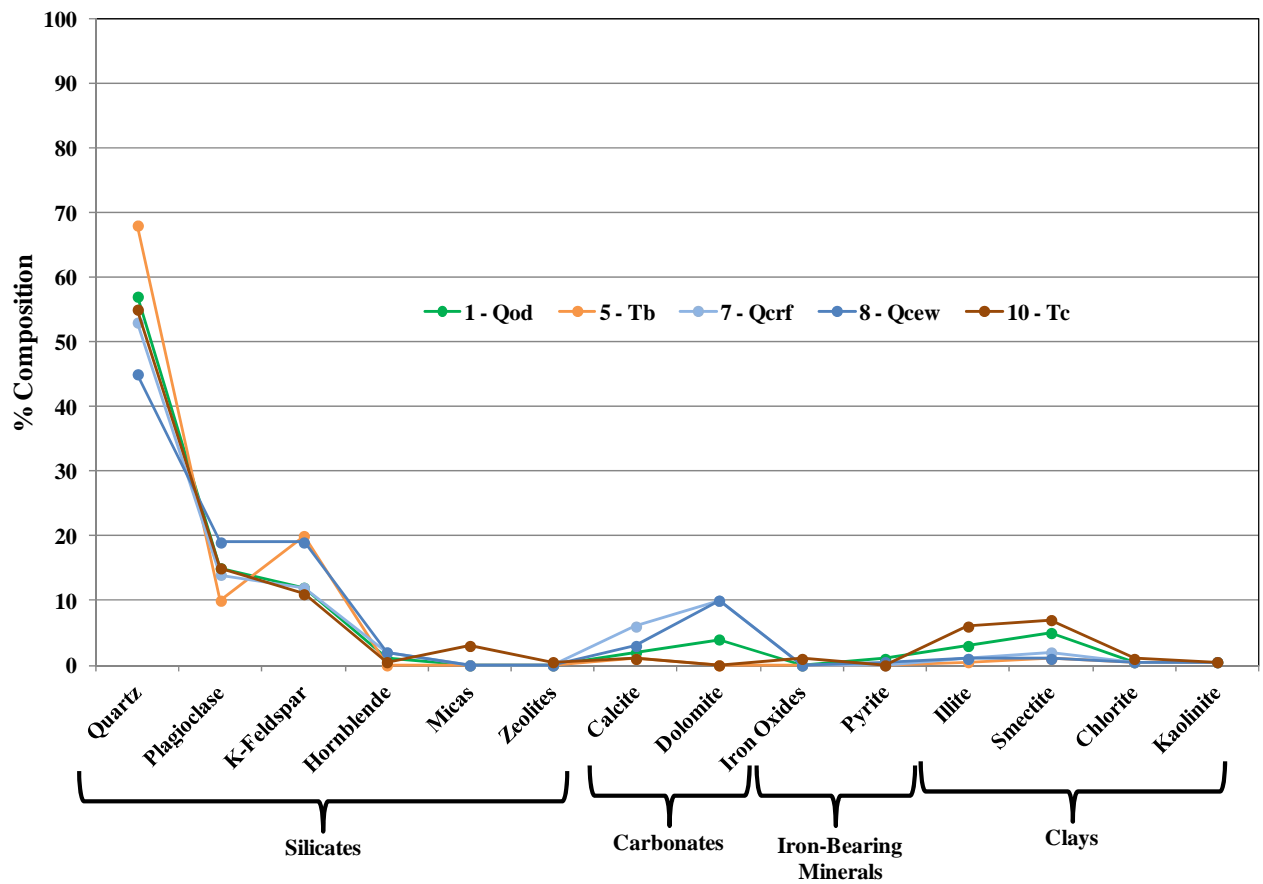


Figure 30. Detailed X-Ray Diffraction (XRD) mineralogical analyses for selected sand deposits in North Dakota.

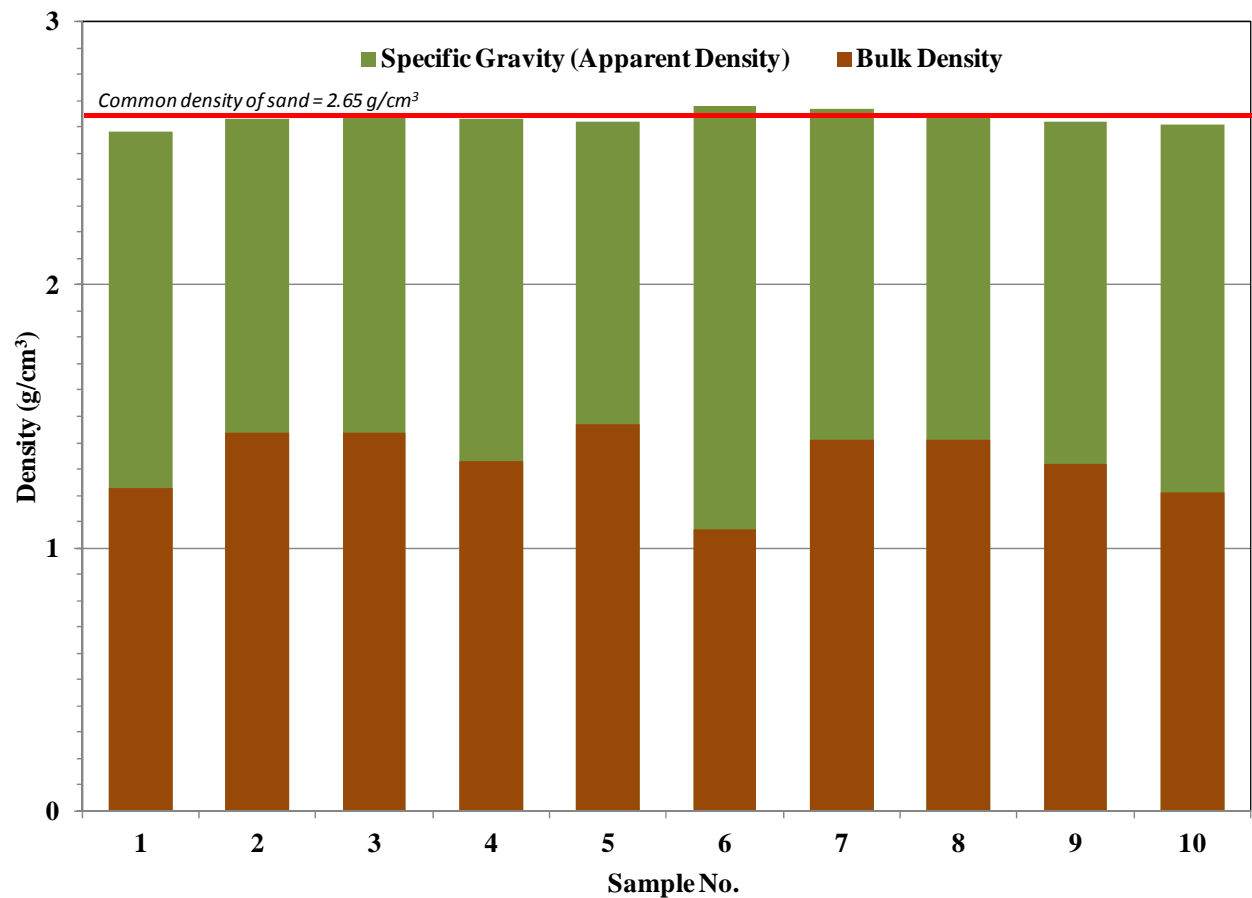


Figure 31. Comparison of Specific Gravity (apparent density) and Bulk Density values for selected sand deposits tested for characterization as proppants in North Dakota.

Silicates

Silicate minerals reported included: Quartz, Plagioclase, K-Felspar, Hornblende, Micas, and Zeolites (i.e. Clinoptilolite).

Quartz sand was the major mineralogical component with samples ranging from 45 to 68% followed by lower amounts of Feldspars ranging from 10 to 19% with lesser amounts of Hornblende (~2%) in sample Nos. 1, 7, and 8 and Micas (3%) reported in sample No.10 from the Cannonball Formation.

In terms of comparative sedimentary petrology, these silicate compositions would be consistent with that of a Feldspathic Arenite, owing to the slightly less than 90% quartz content in the samples.

Carbonates

Carbonate minerals reported included Calcite and Dolomite ranging from 1 to 6% and 4 to 10% respectively. Dolomite was not reported in Tertiary age bedrock sands collected from the Bullion Creek and Cannonball Formations.

Iron-Bearing Minerals

Iron-Bearing minerals reported included Iron Oxides and Pyrite reported at low-level amounts of 1% in sample No. 1 collected from the Denbigh Dunes and sample No. 10 collected from the Cannonball Formation in southern Burleigh County.

Clays

Clay minerals reported included: Illite, Smectite, Chlorite, and Kaolinite. Illites (trace amounts to 6%) and Smectites ranging from one to 7% were the dominant clay minerals reported with trace amounts of Chlorite and Kaolinite noted.

Bulk Density

The bulk density of a proppant describes the mass that fills a unit volume and includes both the proppant and the void space (i.e. porosity) in the sample and is commonly used for determining the mass of proppants required to fill fractures, a storage vessel, or in completing general volume estimates. The bulk density of selected sands tested in North Dakota for potential use as a proppant (Figure 30) ranged from 1.07 to 1.47 g/cm³ with an to 2.40 g/cm³.

Specific Gravity

The specific gravity (i.e. apparent density) of a sand is another measure of potential proppant density that *includes* the void or pore space that is inaccessible to the testing fluid, which is a low-viscosity oil that wets the particle pore spaces. The specific gravity of selected sands tested in North Dakota for use as proppant (Figure 30) ranged from 2.58 to 2.68 grams per cubic centimeter (g/cm³) with an average of 2.63 g/cm³. The specific gravity of sand on average is 2.65 g/cm³ (Olhoeft and Johnson, 1989).

CONSIDERATIONS FOR SAND PROCESSING

The likely technical challenge for extracting a marketable volume of potential proppant sand from local sources will most likely result in the generation of significant volumes of material of coarser grades that would need to have a market demand in order to fully utilize and develop the sand deposit resource along the proppant generation path. Treating marginal quality sands as a type of “low-grade ore” with a suitable plant-processing model that includes a proppant sand beneficiation pathway may help in developing an overall economic proppant sand processing model (Wiegel, 2011) that could be successfully implemented in North Dakota. This could include resin coating processes or blending with other “higher quality” proppants.

The following potential proppant sand preparatory process-plant model, which consists of three major processes of 1) sizing, 2) classification, and 3) beneficiation, with both a traditional gravel production pathway and a sand/proppant production pathway is discussed below (Figure 32). Overall, this potential processing model would include seven steps, consisting of three mechanical mass volume reductions and two or three wet refinement treatments aimed specifically at removing low-density materials (e.g. organics and shales) and acid-soluble (i.e. carbonates) components. This type of potential process model could be considered when attempting to evaluate or produce sand sourced from a location in North Dakota for use as a natural sand proppant for the hydraulic fracturing of oil and gas wells.

Possible sand and gravel processing steps to produce natural sand proppant from sands sourced in North Dakota:

1. Mechanical Separation(s) to Initial Sand Size Fractions (Bulk) – Volume Reduction Step.
2. Fluid Wash for Fines Removal – Volume Reduction Step.
3. Mechanical Sorting for Transfer of Materials through the Traditional Gravel or Sand/Proppant Production Path – Volume Reduction Step.
4. Density Separation (e.g. jiggling or floating) – Volume Reduction Step.
5. Sizing (Classification) to Selected Proppant Sand Sizes – Volume Reduction Step.
6. Strong Acid Wash or Washes for Acid Soluble Mass Removal (i.e. carbonates, iron oxides) – Volume Reduction and Material Refinement Step.
7. Additives treatment for enhancement of desired properties (e.g. resin coating, blending with high-strength proppants) – Material Refinement Step.

There may be several benefits to processing in different configurations depending on numerous factors, such as cost, equipment availability, and time. There are likely several processing configurations that could potentially render a marginal source material useable under a variety of different fracture stimulation project designs, specifications, and configurations.

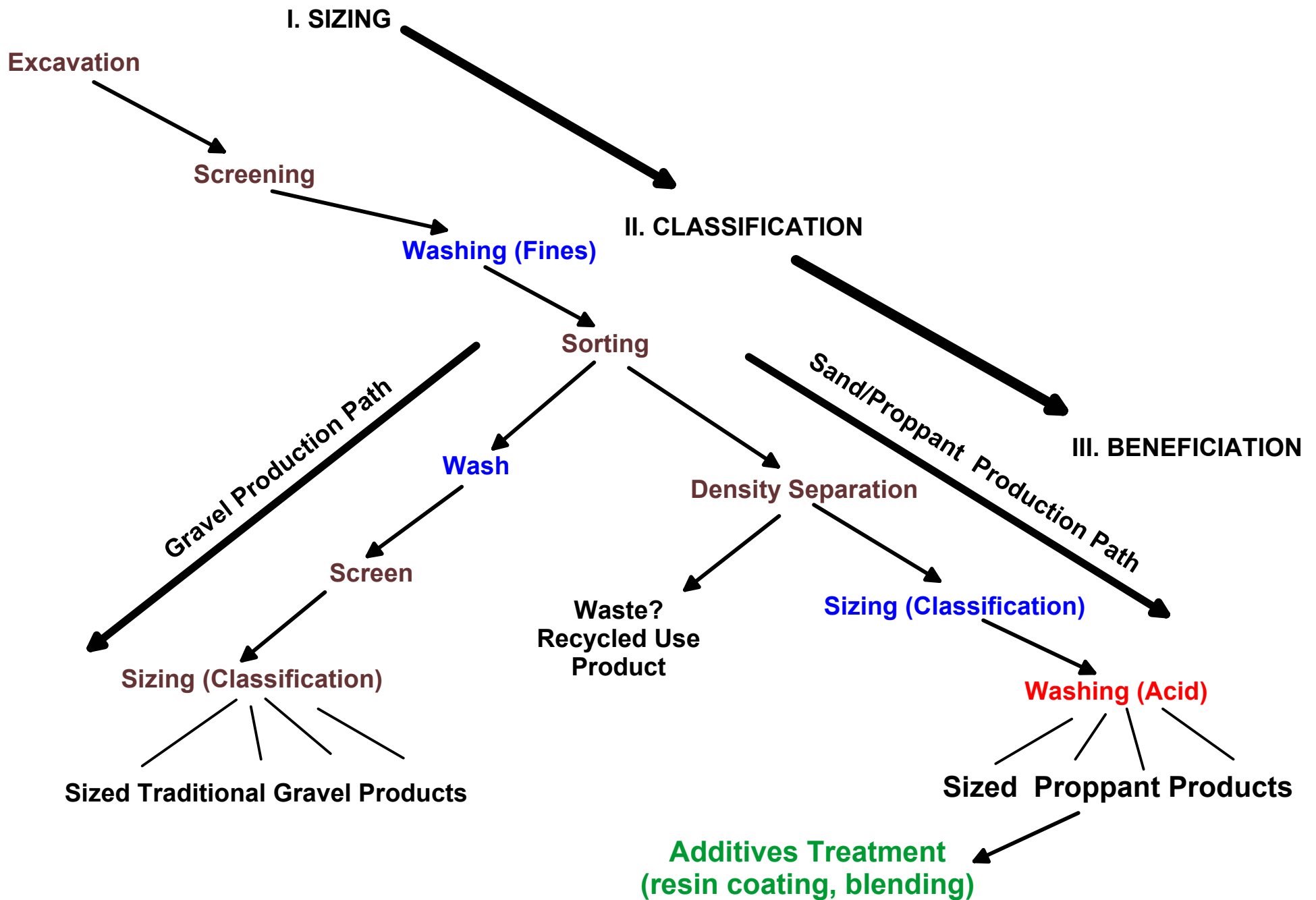


Figure 32. Possible sand & gravel plant processing flowsheet for the production of natural sand proppant for sands sourced in North Dakota. Mechanical steps are highlighted in brown, wet (water required) steps in blue, chemical solution steps in red, and additives treatment in green.

CONCLUSIONS

Selected North Dakota sand deposits were sampled and tested for potential use as natural sand proppants in the hydraulic fracturing of oil and gas wells in the Williston Basin during the 2009 to 2011 biennium. Testing and sediment characterization indicate that North Dakota's sand resources are of a condition and quality that approach current industry standards, specifications, and recommendations for the use of natural sands as proppants. However, they are of a lesser overall quality in direct comparison with other domestic sand sources currently being utilized as proppant in the U.S., such as Ottawa "white" and Brady "brown" type sands. Significant processing and material refinement would likely be required to bring deposits of marginal quality up to applicable standards and specifications. Creativity in proppant design formulations and manufacture may render North Dakota's sand deposits viable. That may be made possible through the deposit refinement process during production, material enhancement (such as resin coating or blending with ceramic proppants), reduction in standards of quality and use based on overall sand resource availability, or enhancements in other areas of the hydraulic fracturing design formula. The information contained in this report will also find use in the continued characterization of North Dakota's sand (and gravel) resources for use in other industrial applications.

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APPENDICIES

APPENDIX I – Testing Specifications and Recommendations for Natural Sand Proppants.

APPENDIX II – Bulk Sample Grain-Size Distribution Diagrams.

APPENDIX III – Sized Sample Grain-Size Distribution Diagrams.

APPENDIX I. Testing Specifications and Recommendations for Natural Sand Proppants.

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

Grain-Size Distribution (Sieve Analysis)

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

Sphericity and Roundness (Particle Shape Factors)

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

Acid Solubility

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

Turbidity

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

Crush Resistance

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

Mineralogy

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

APPENDIX II. Bulk Sample Grain-Size Distribution Diagrams.

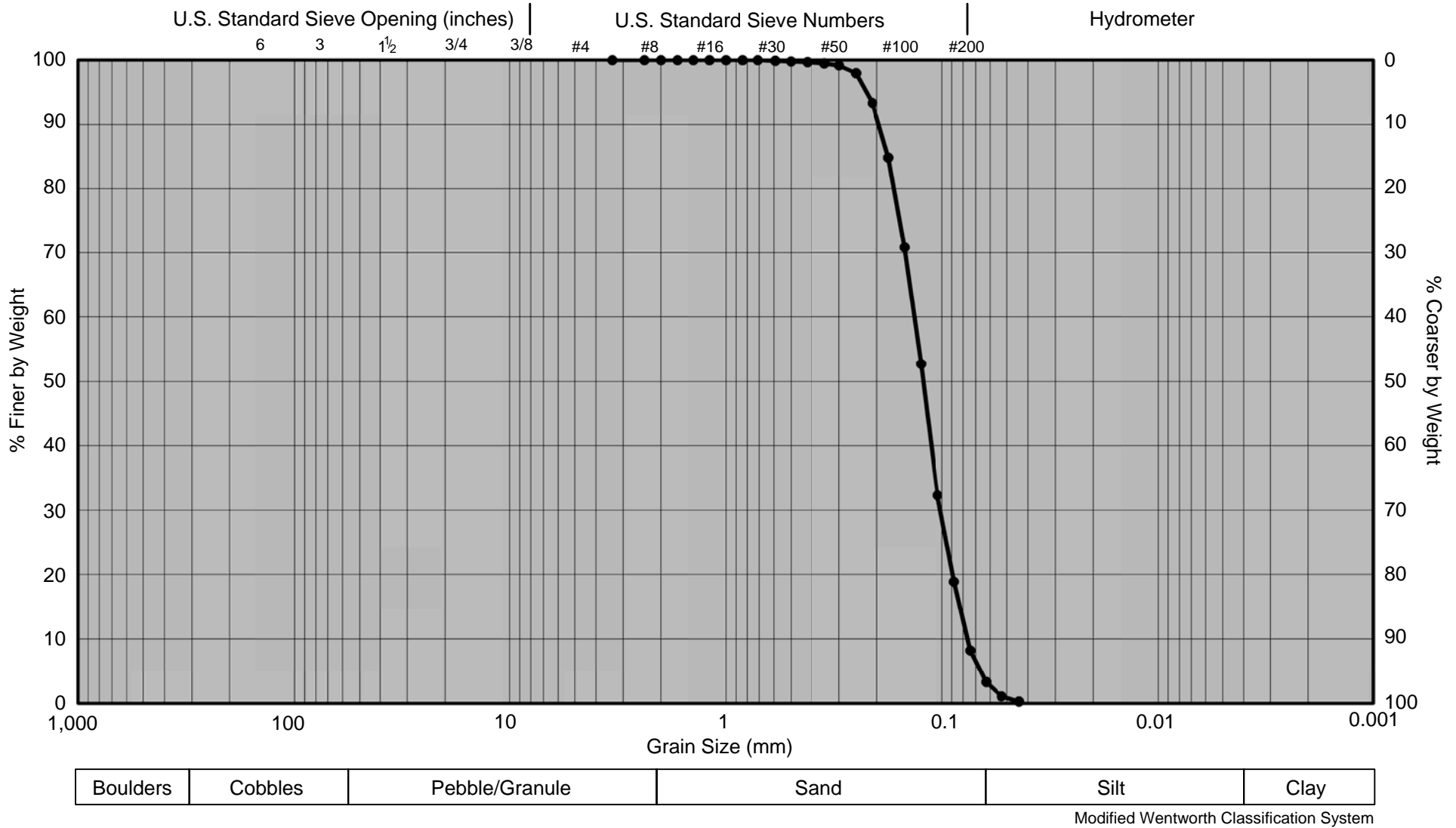


Figure A-II-1. Bulk Sample Grain-Size Distribution Diagram for Sample No. 1 - Qod.

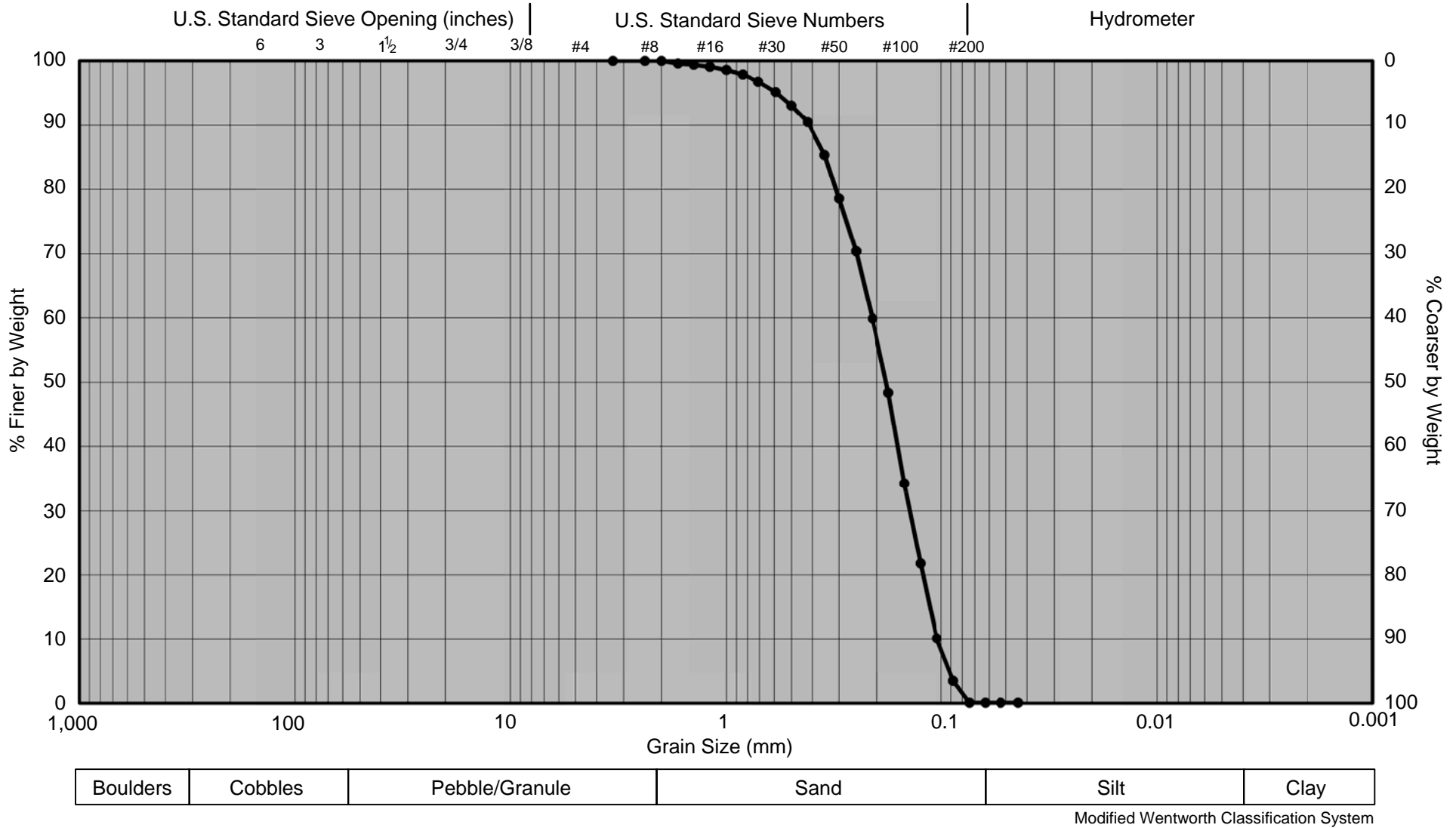


Figure A-II-2. Bulk Sample Grain-Size Distribution Diagram for Sample No. 2 - Qcrh.

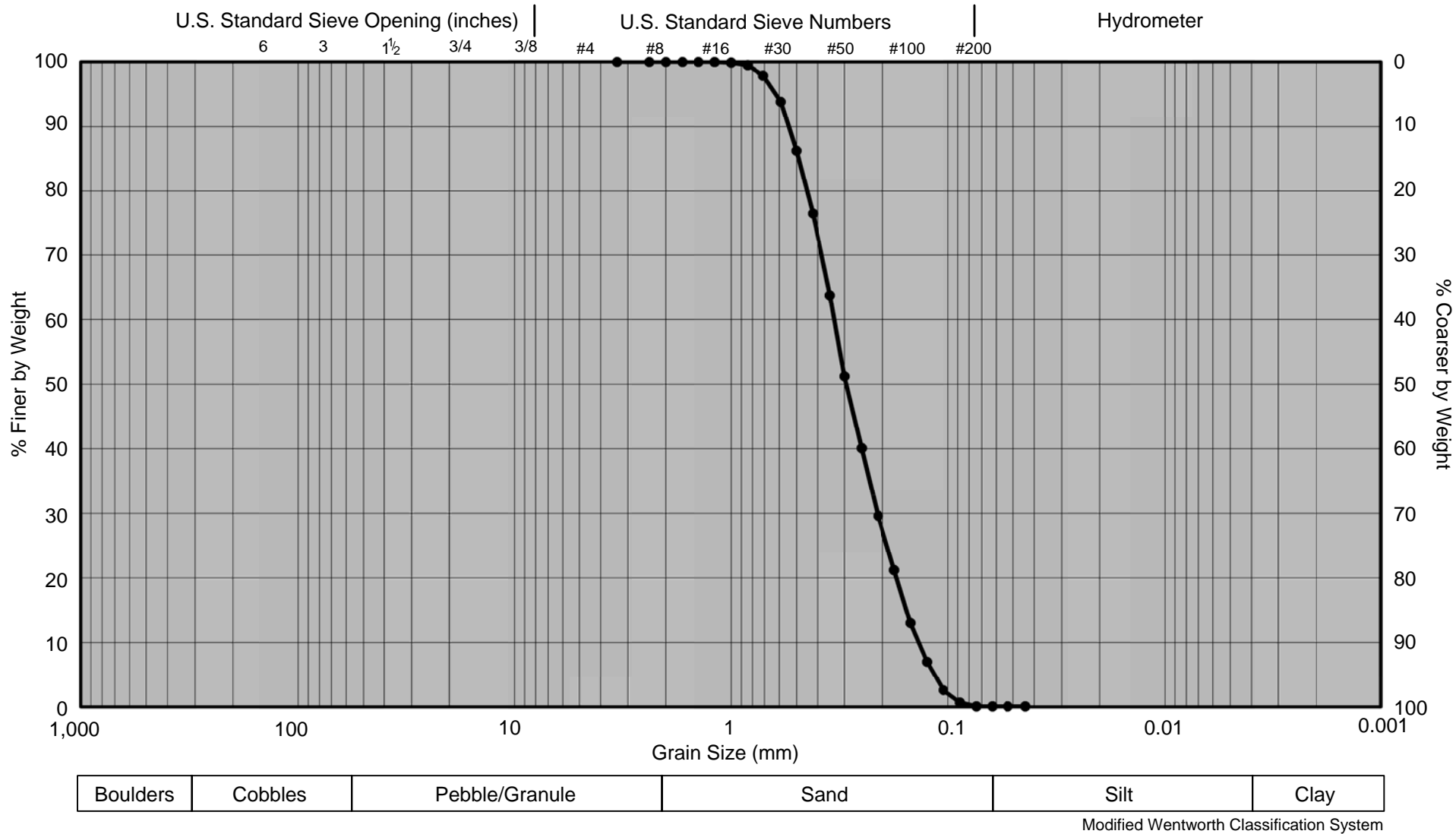


Figure A-II-3. Bulk Sample Grain-Size Distribution Diagram for Sample No. 3 - Qtou.

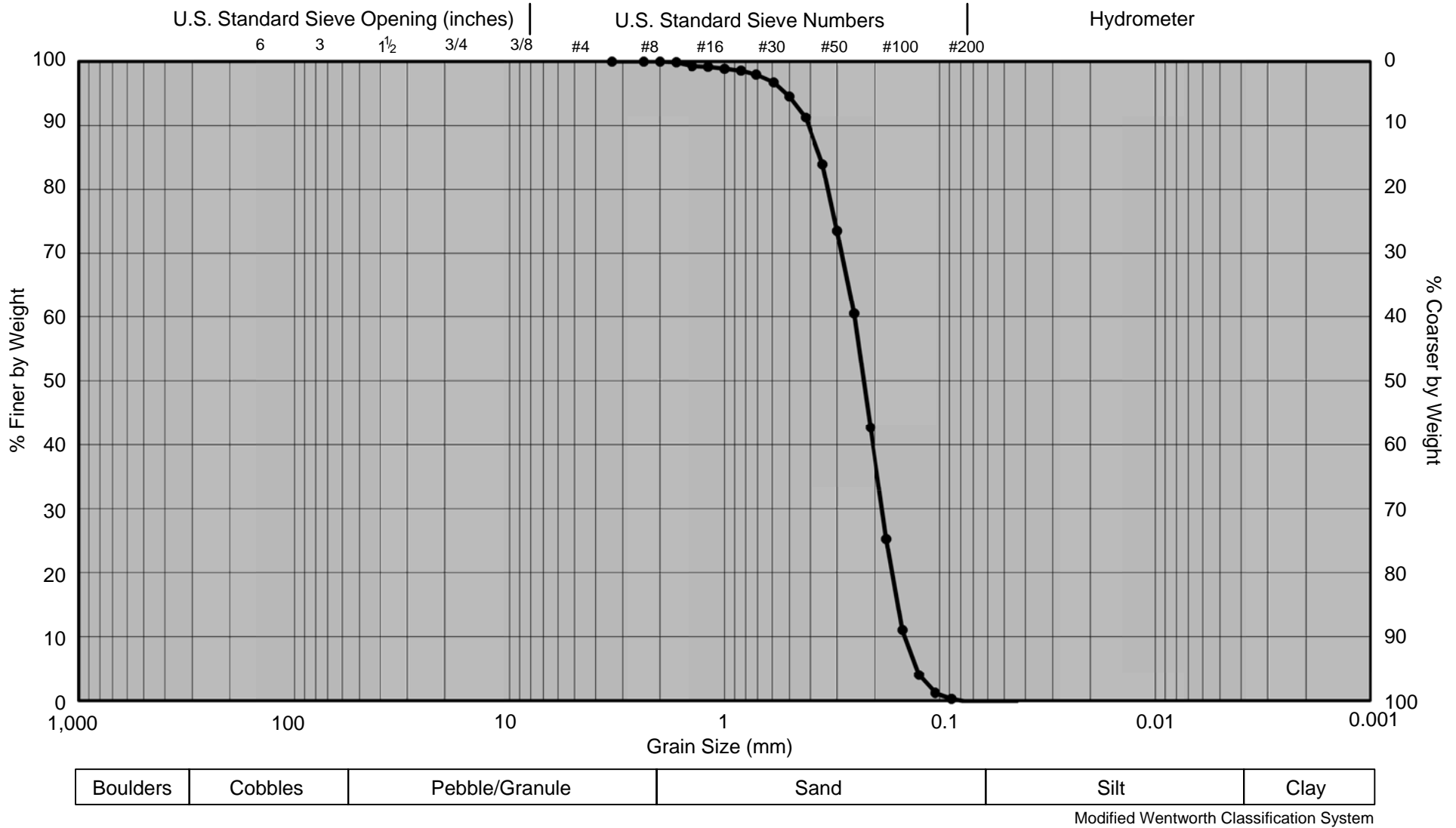


Figure A-II-4. Bulk Sample Grain-Size Distribution Diagram for Sample No. 4 - QTu.

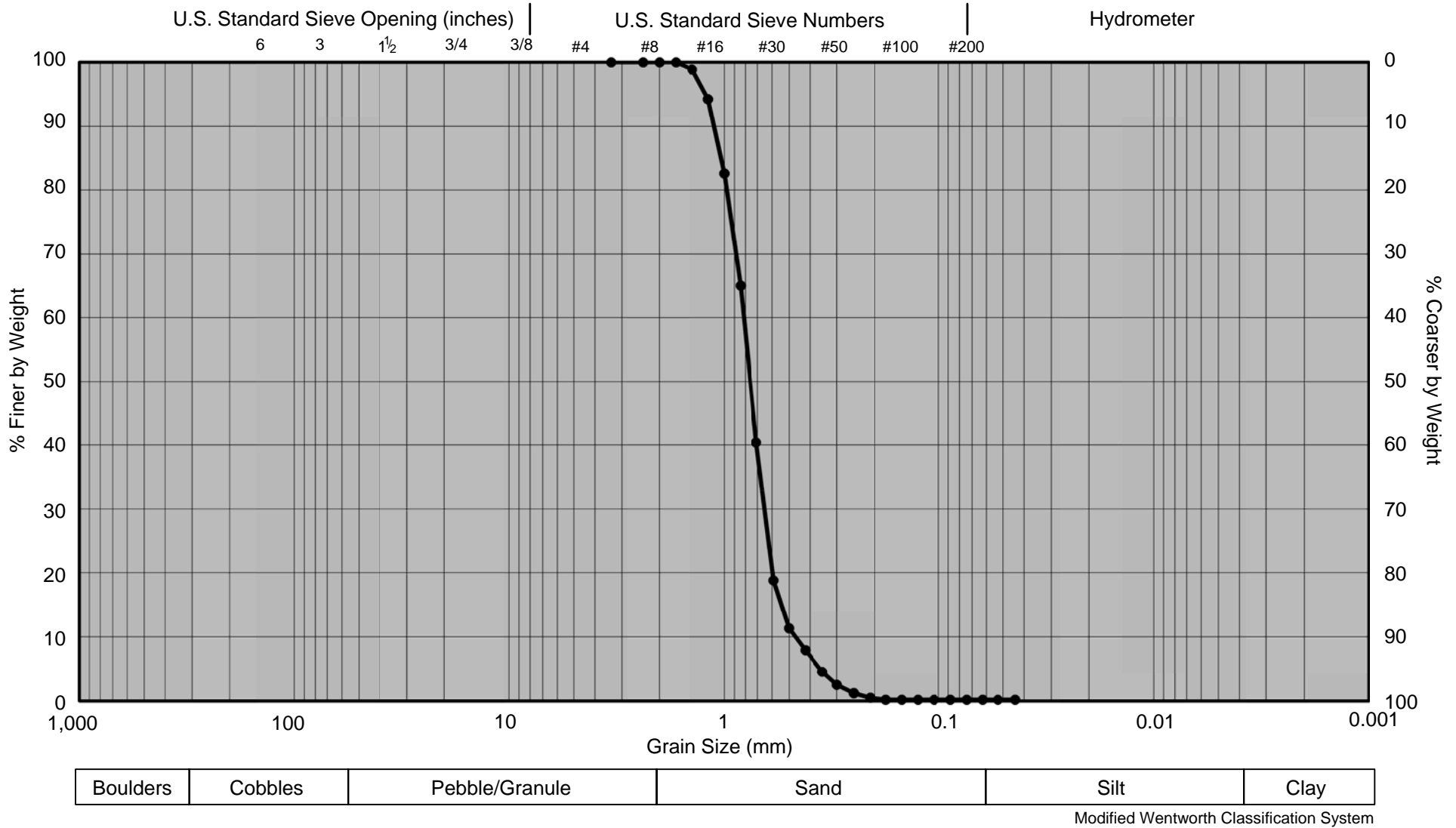


Figure A-II-5. Bulk Sample Grain-Size Distribution Diagram for Sample No. 5 - Tb.

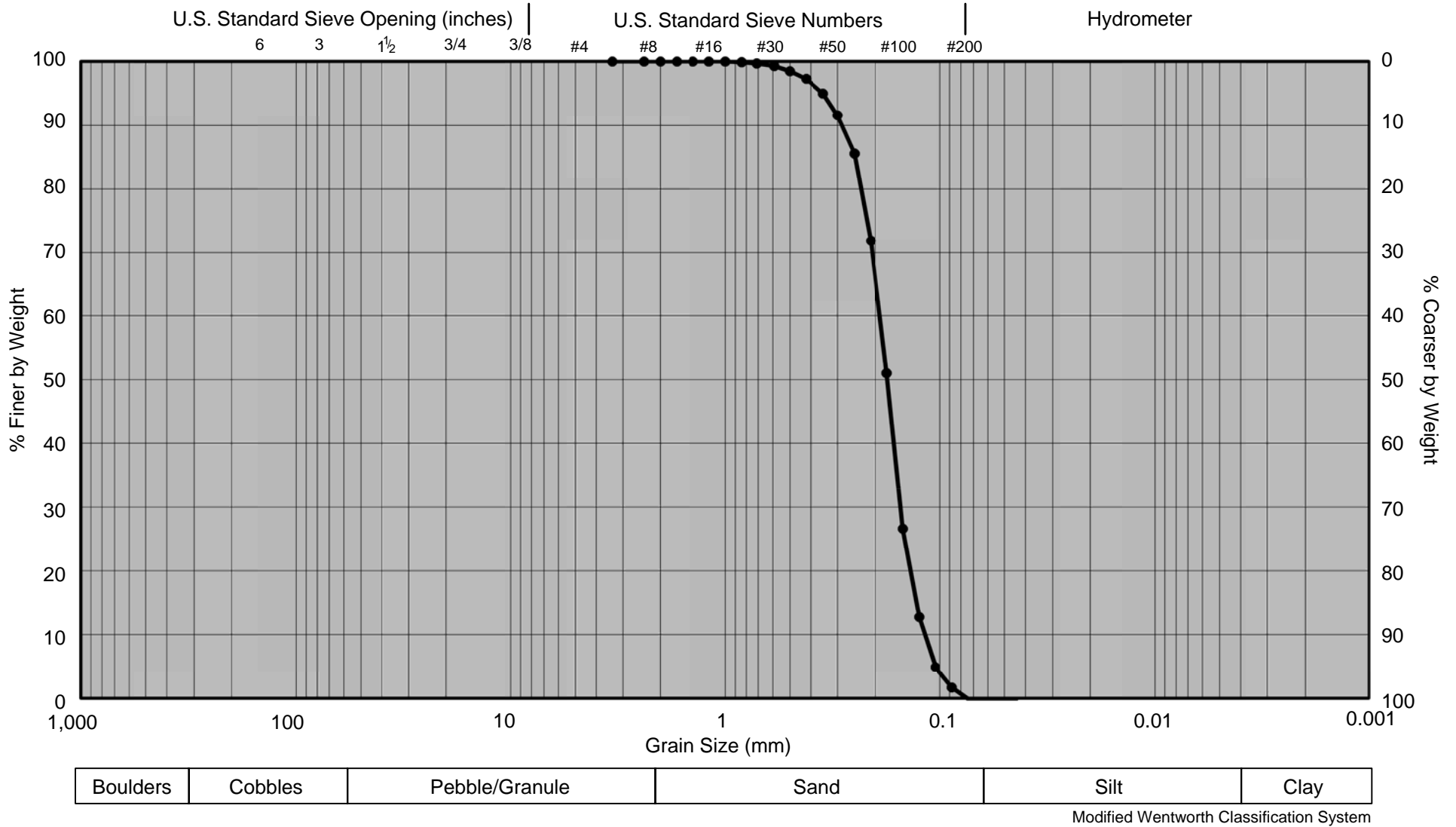


Figure A-II-6. Bulk Sample Grain-Size Distribution Diagram for Sample No. 6 - Tb.

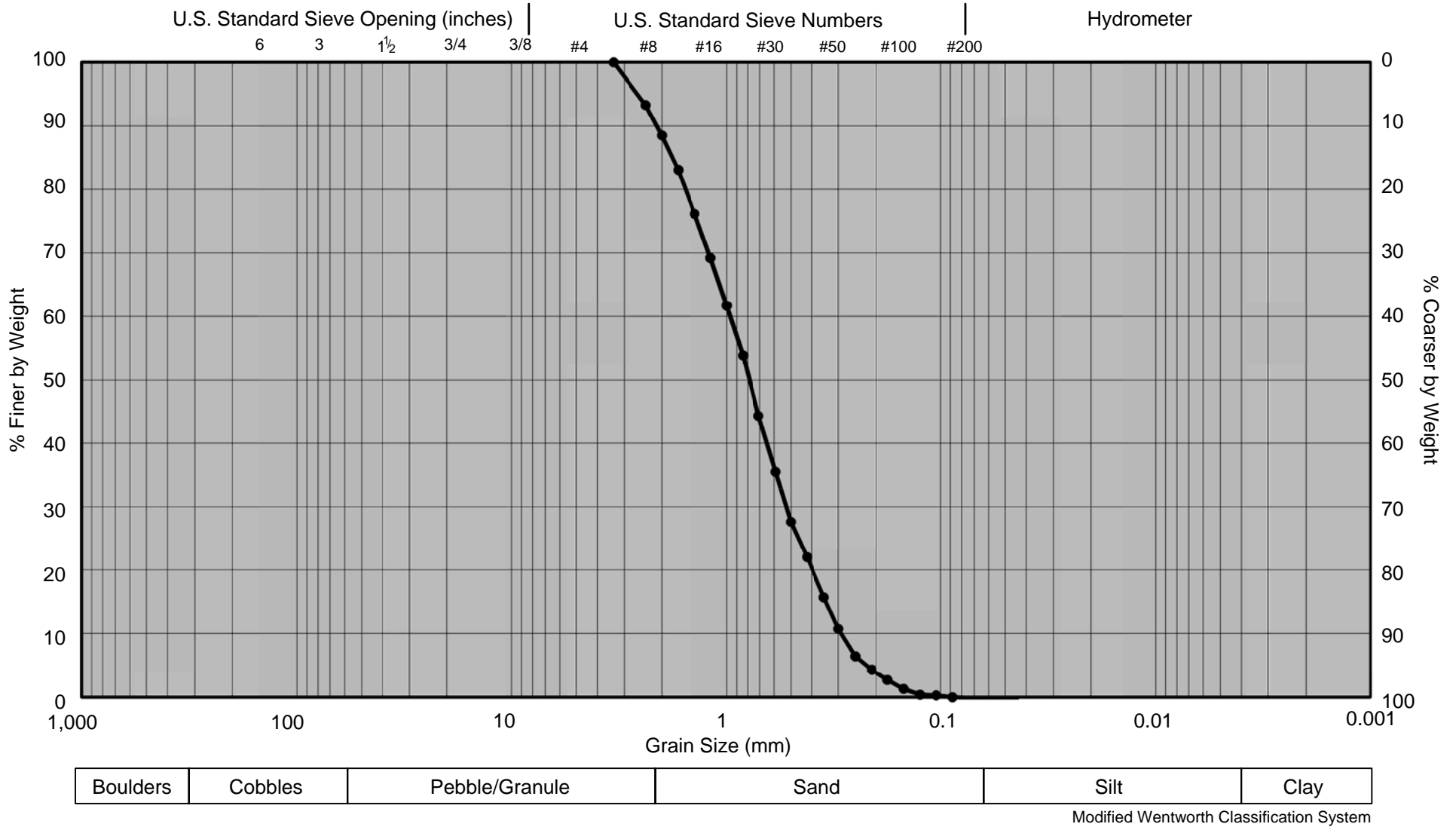


Figure A-II-7. Bulk Sample Grain-Size Distribution Diagram for Sample No. 7 - Qcrf.

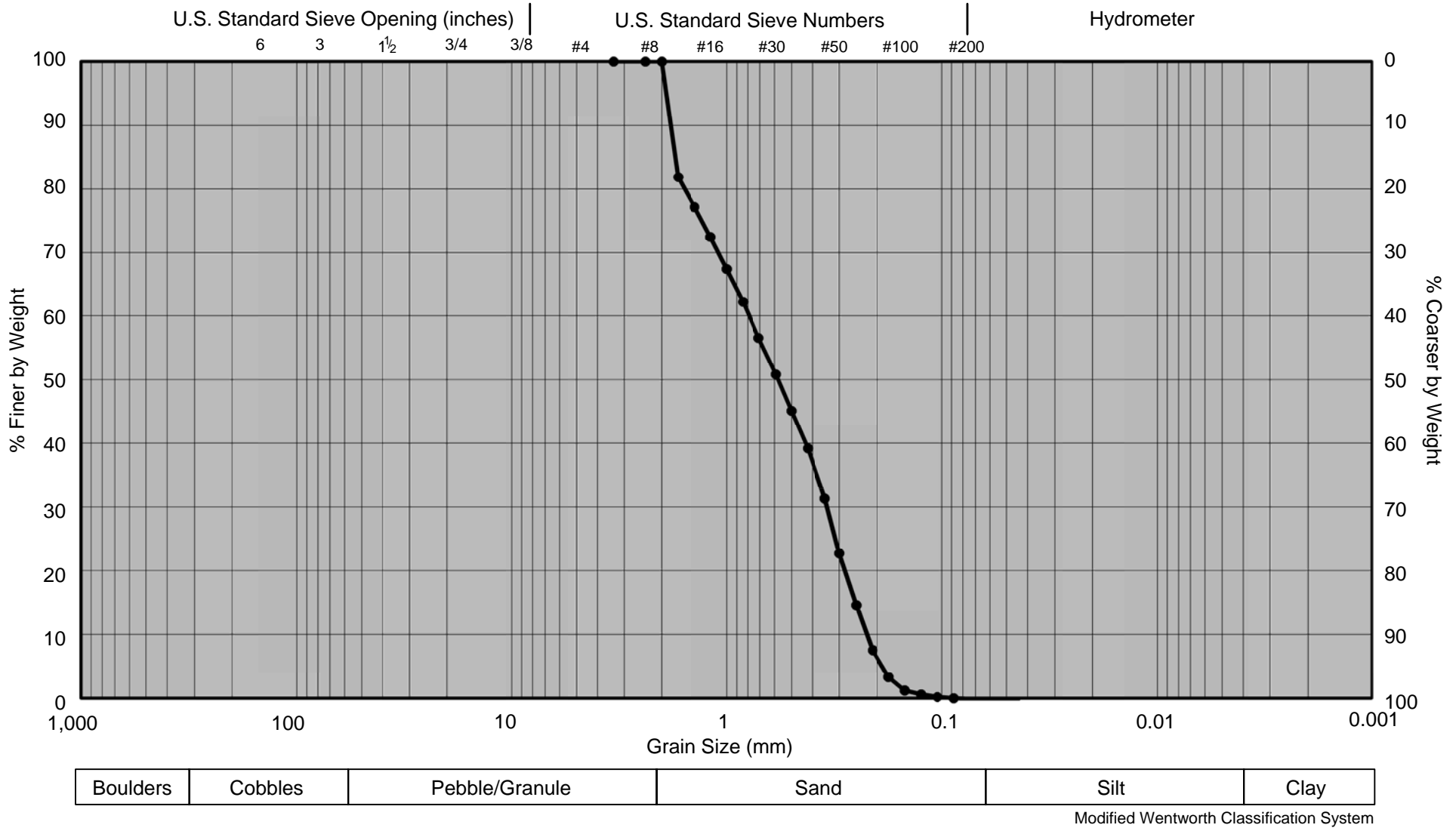


Figure A-II-8. Bulk Sample Grain-Size Distribution Diagram for Sample No. 8 - Qcew.

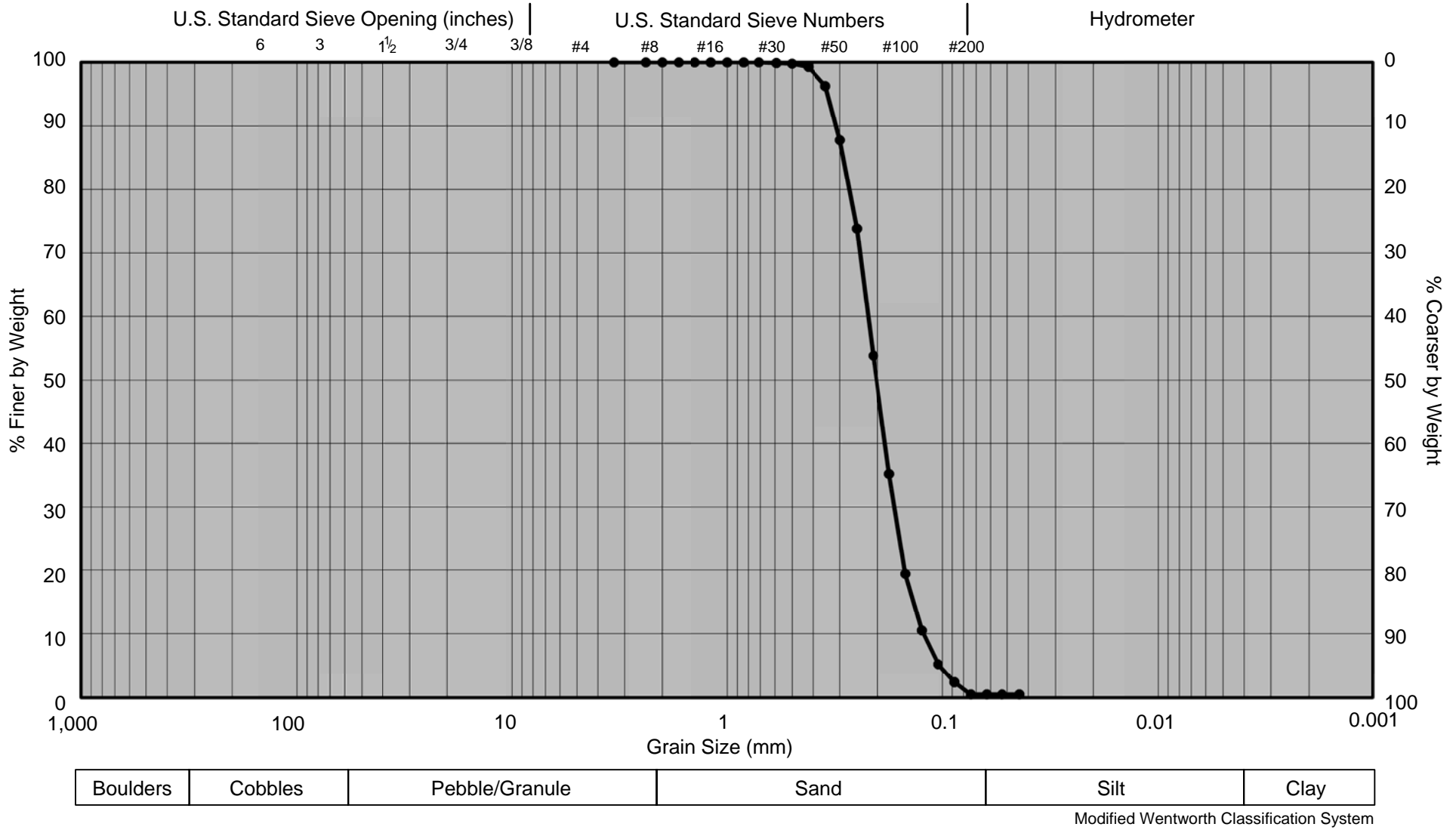


Figure A-II-9. Bulk Sample Grain-Size Distribution Diagram for Sample No. 9 - Qcdn.

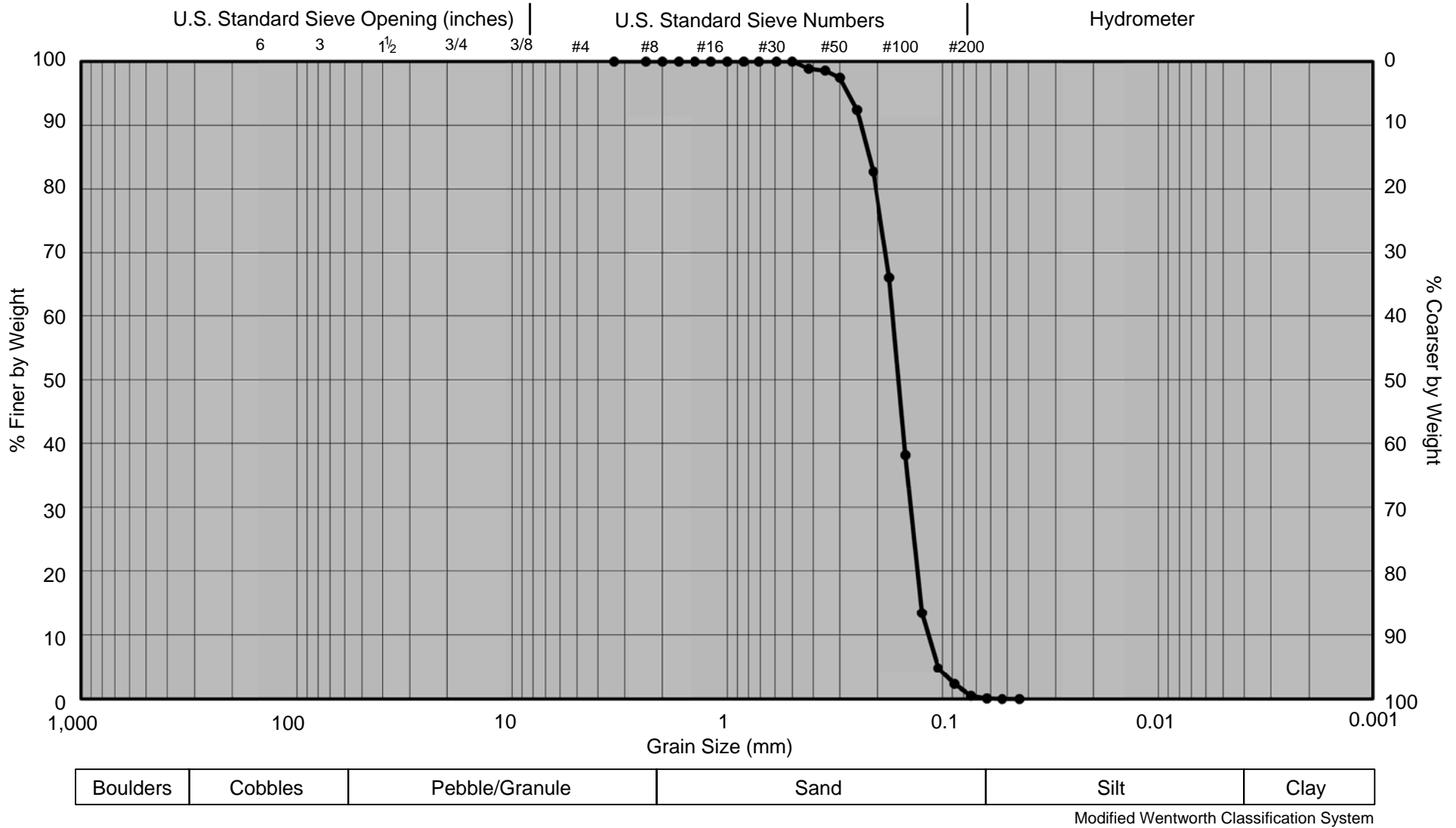


Figure A-II-10. Bulk Sample Grain-Size Distribution Diagram for Sample No. 10 - Tc.

APPENDIX III. Sized Sample Grain-Size Distribution Diagrams.

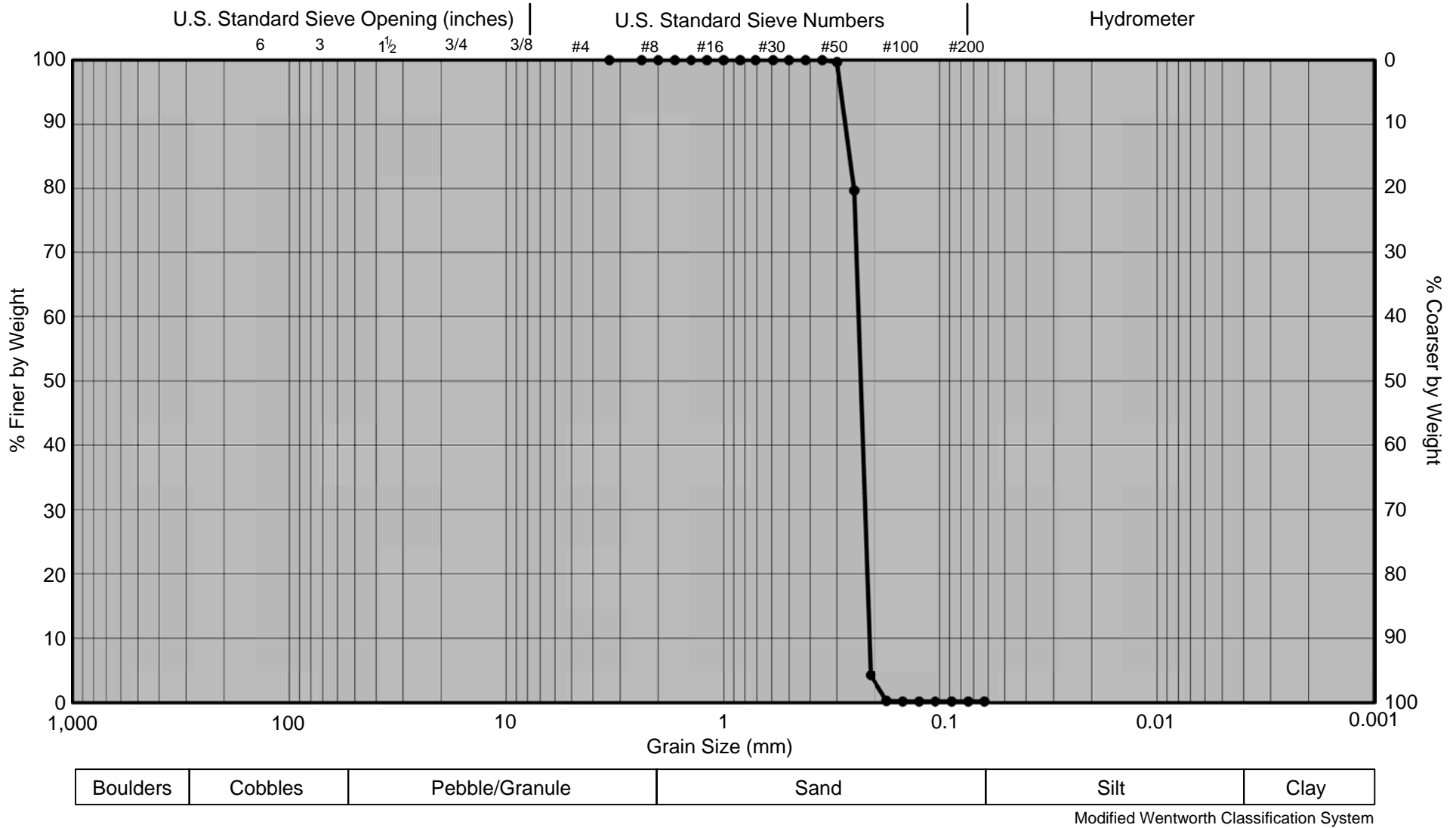


Figure A-III-1. Grain size distribution diagram for Sample No. 1 - Qtou 40/70 Cut.

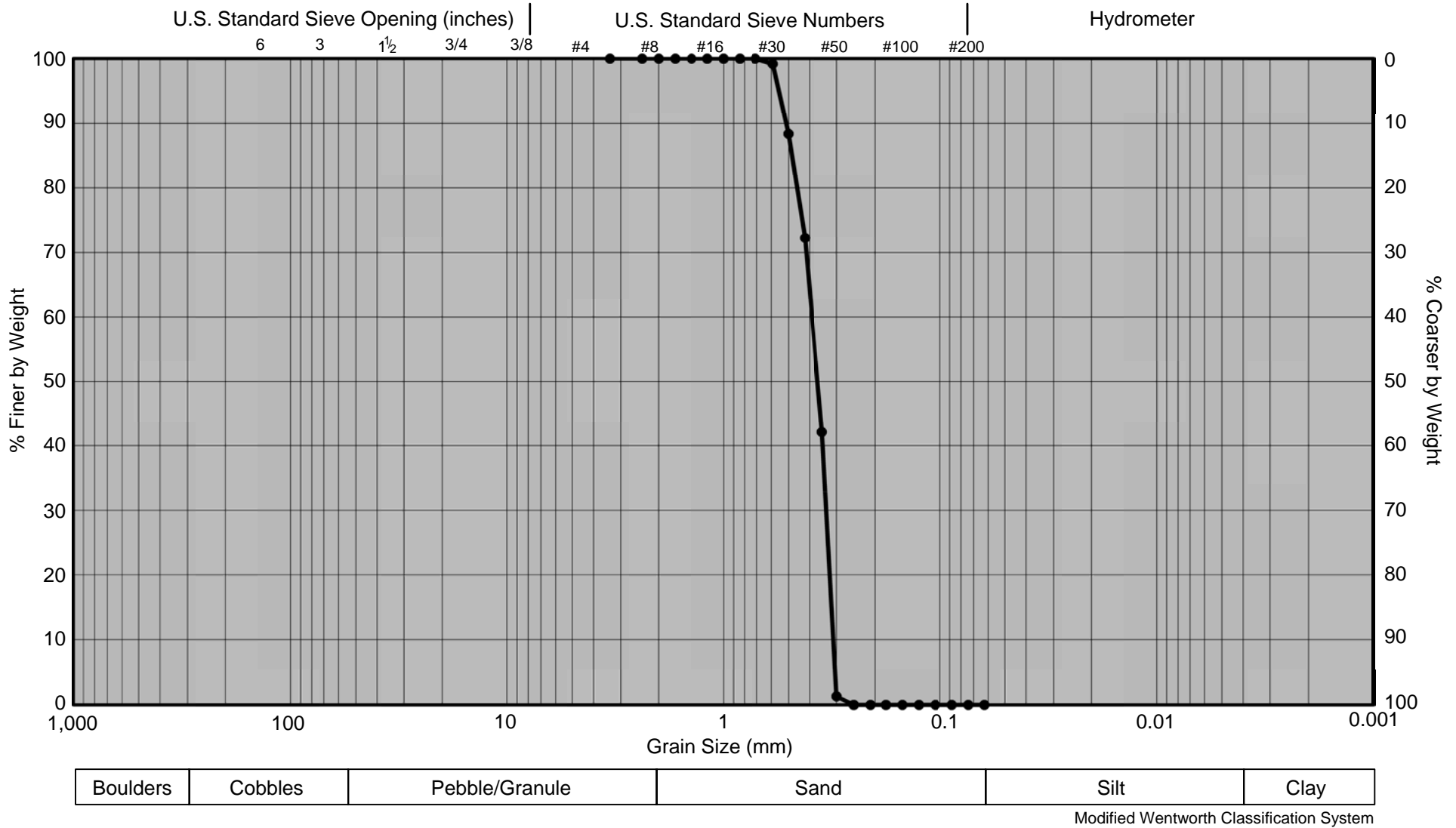


Figure A-III-2. Grain size distribution diagram for Sample No. 2 - Qcrh 30/50 Cut.

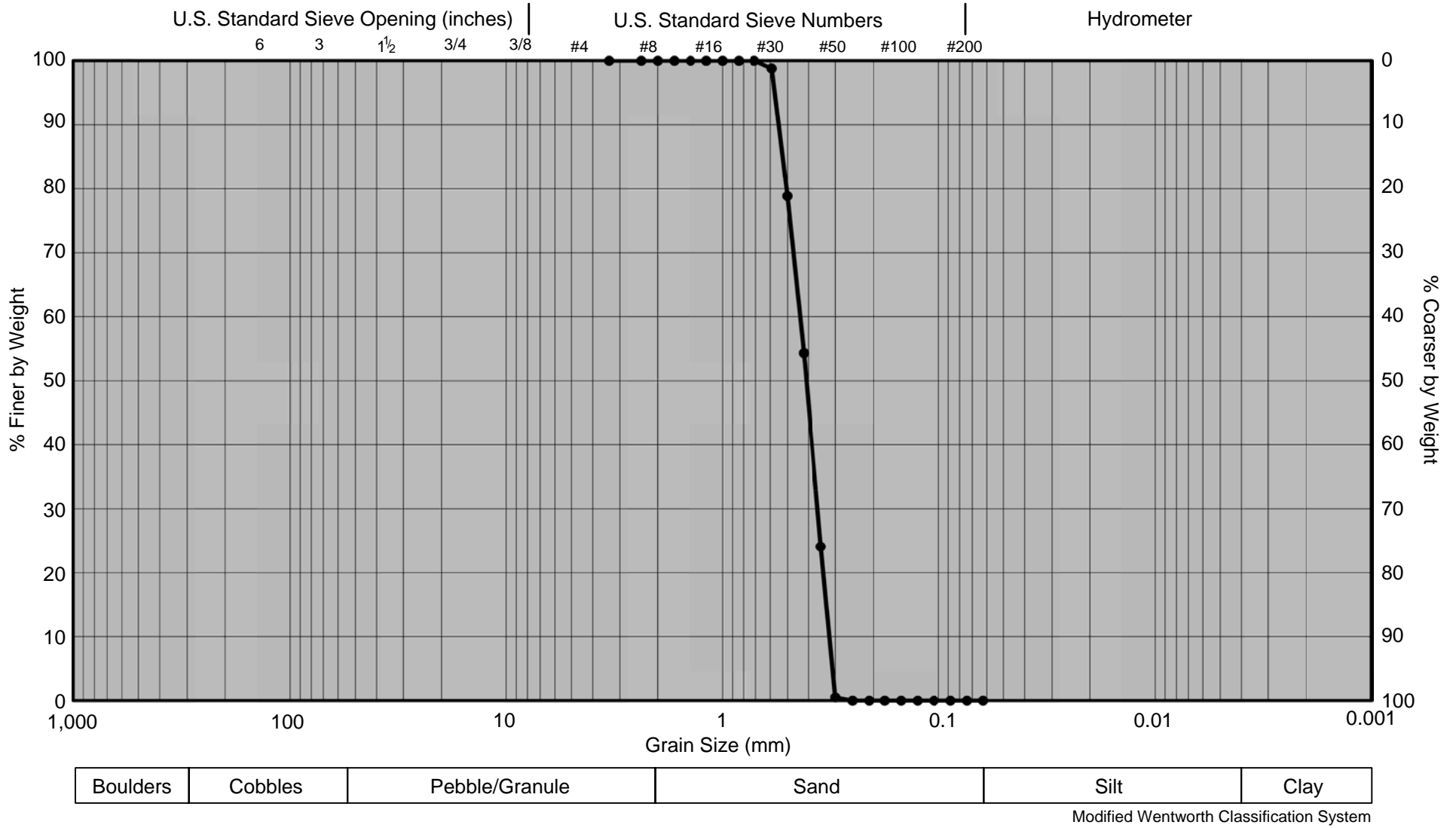


Figure A-III-3. Grain size distribution diagram for Sample No. 3 - Qtou 30/50 Cut.

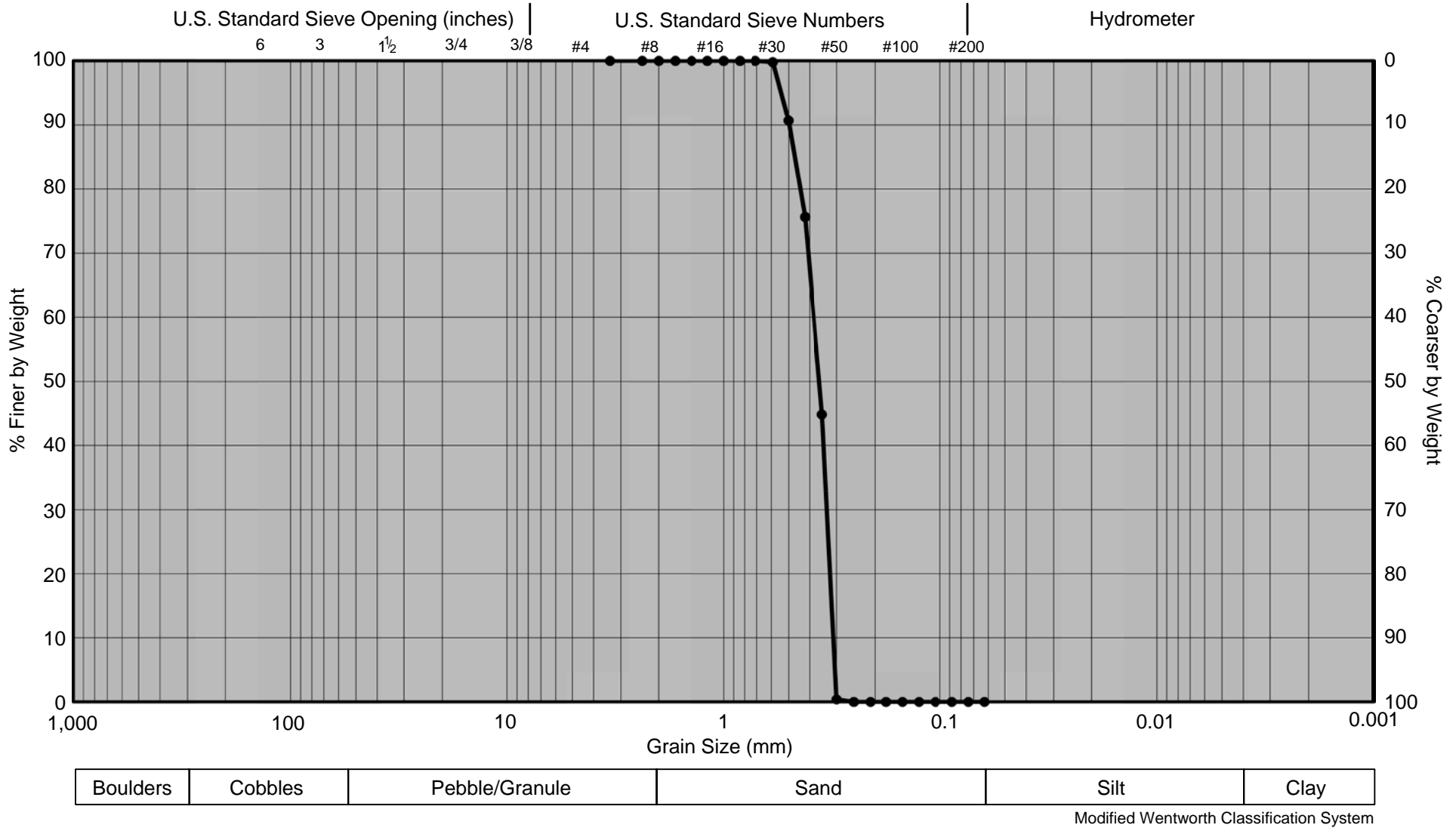


Figure A-III-4. Grain size distribution diagram for Sample No. 4 - QTu 30/50 Cut.

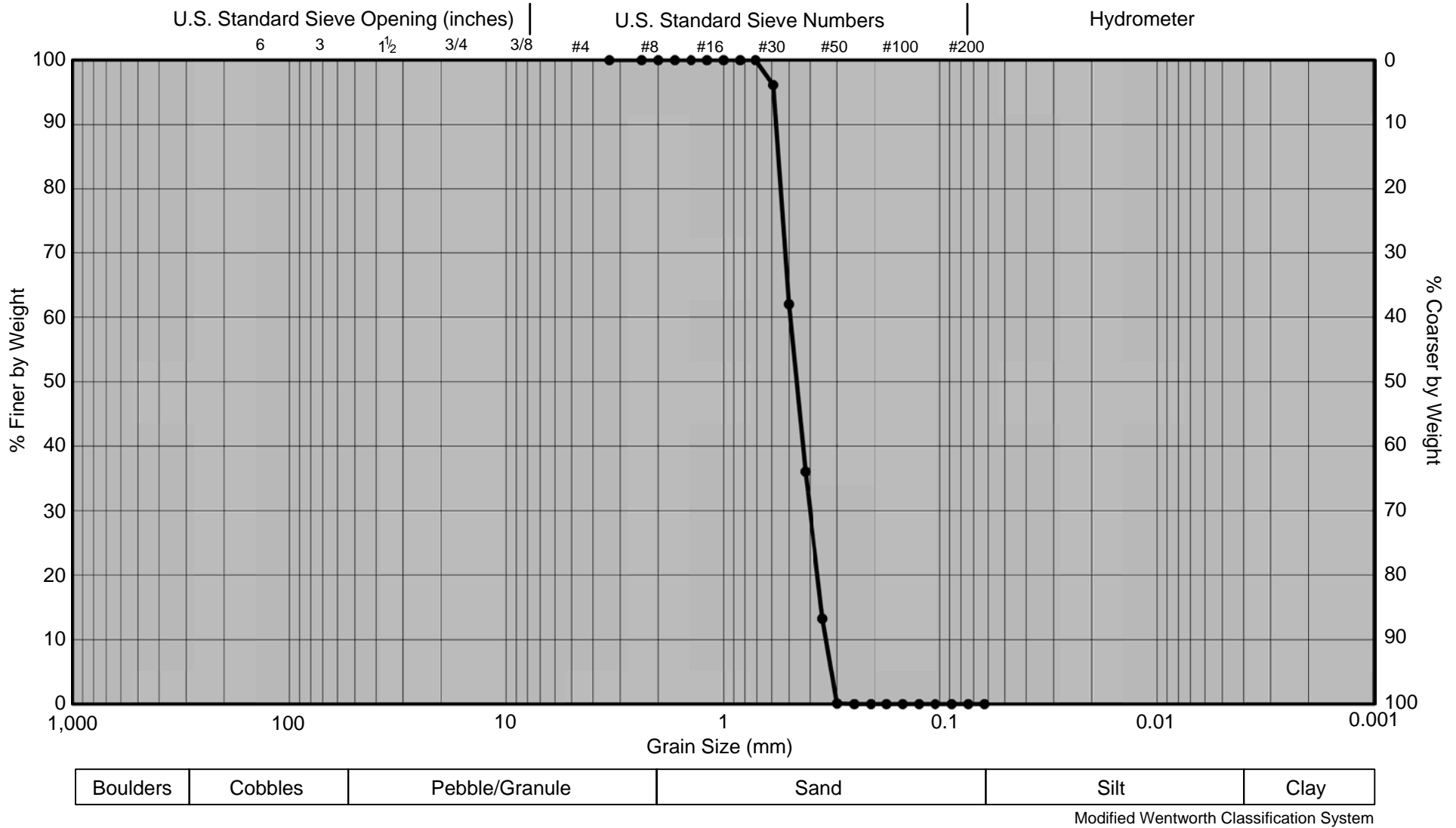


Figure A-III-5. Grain size distribution diagram for Sample No. 5 - Tb 30/50 Cut.

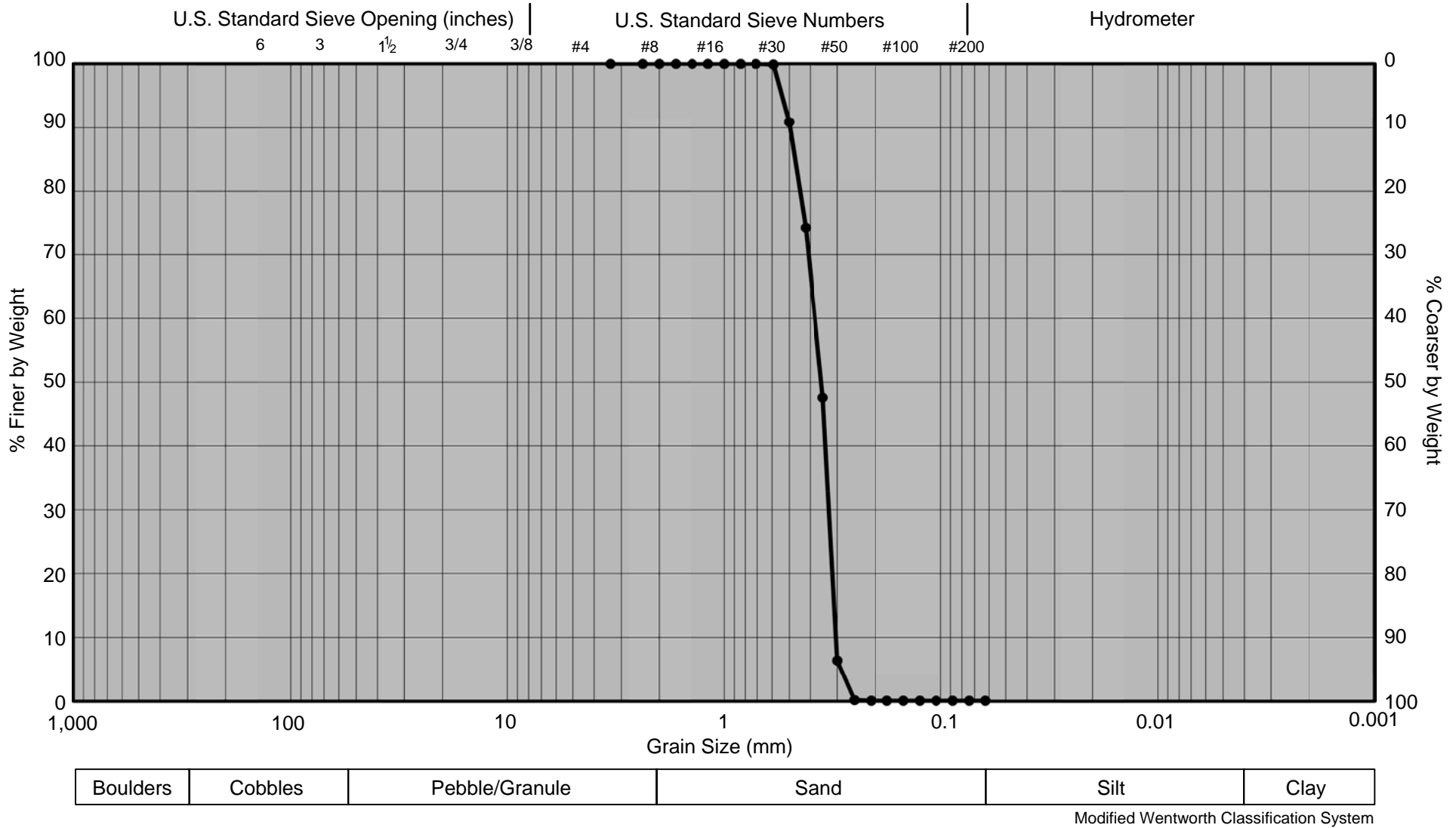


Figure A-III-6. Grain size distribution diagram for Sample No. 6 - Tb 30/50 Cut.

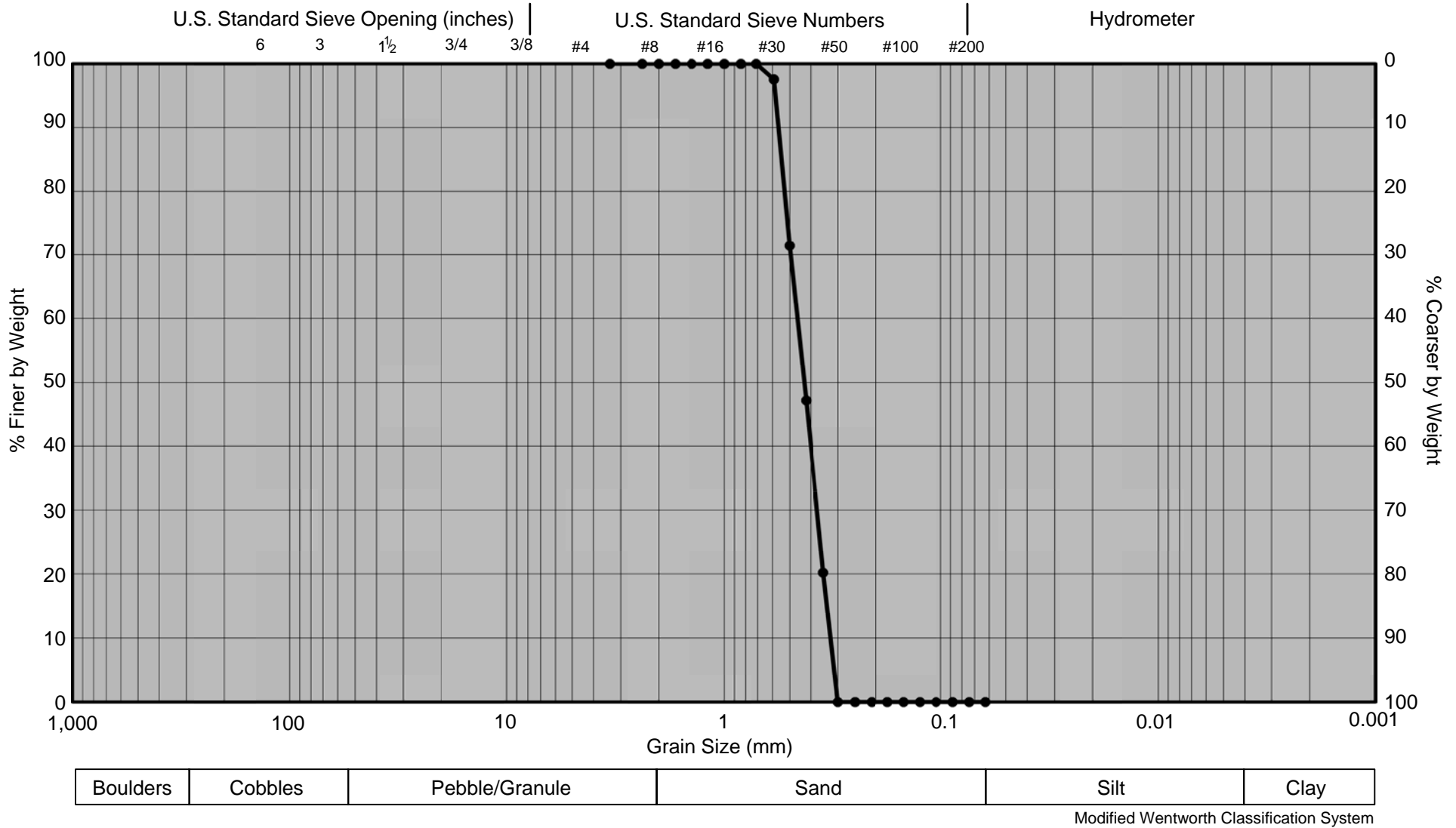


Figure A-III-7. Grain size distribution diagram for Sample No. 7 - Qcrf 30/50 Cut.

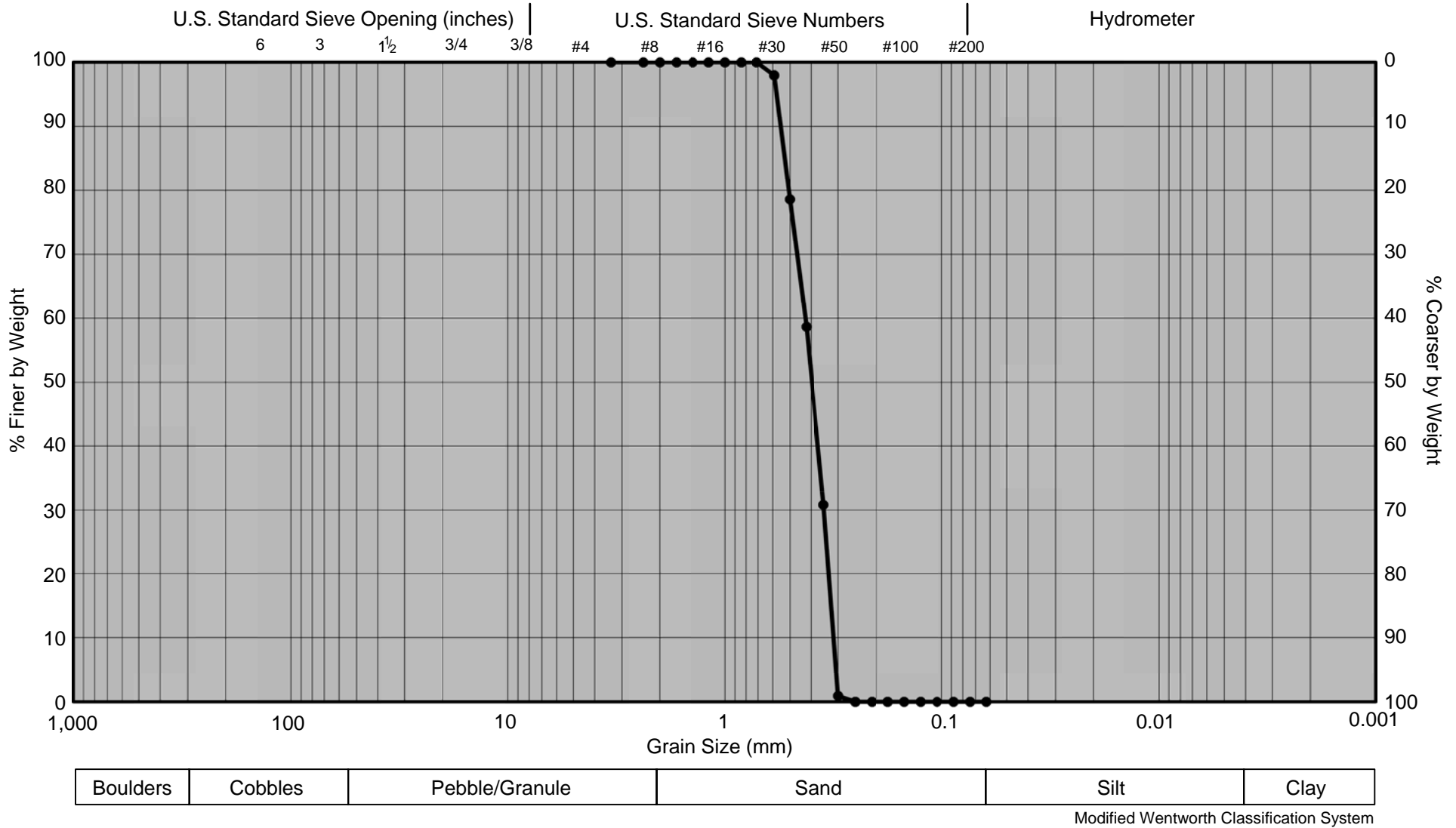


Figure A-III-8. Grain size distribution diagram for Sample No. 8 - Qcew 30/50 Cut.

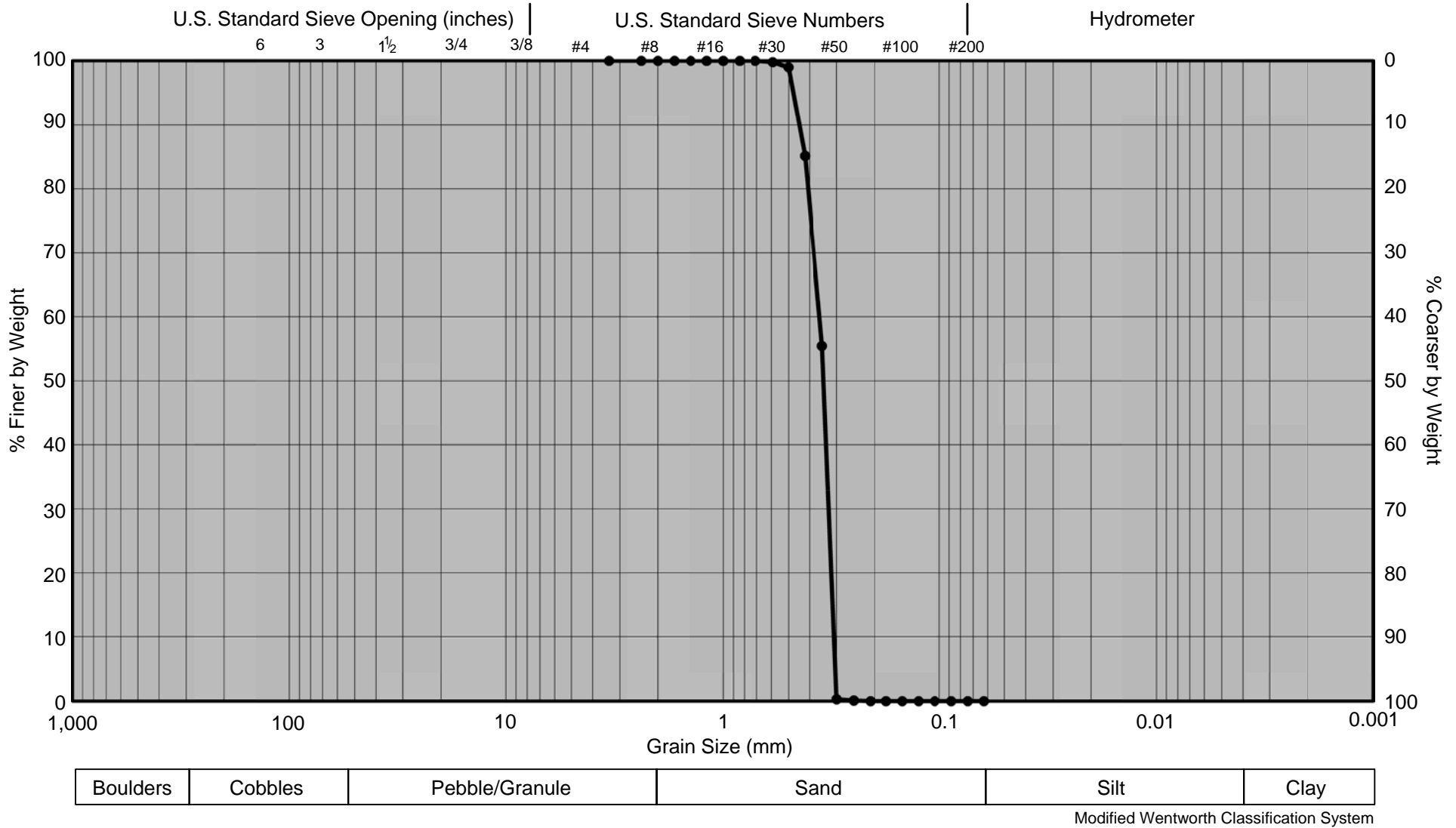


Figure A-III-9. Grain size distribution diagram for Sample No. 9 - Qcdn 30/50 Cut.

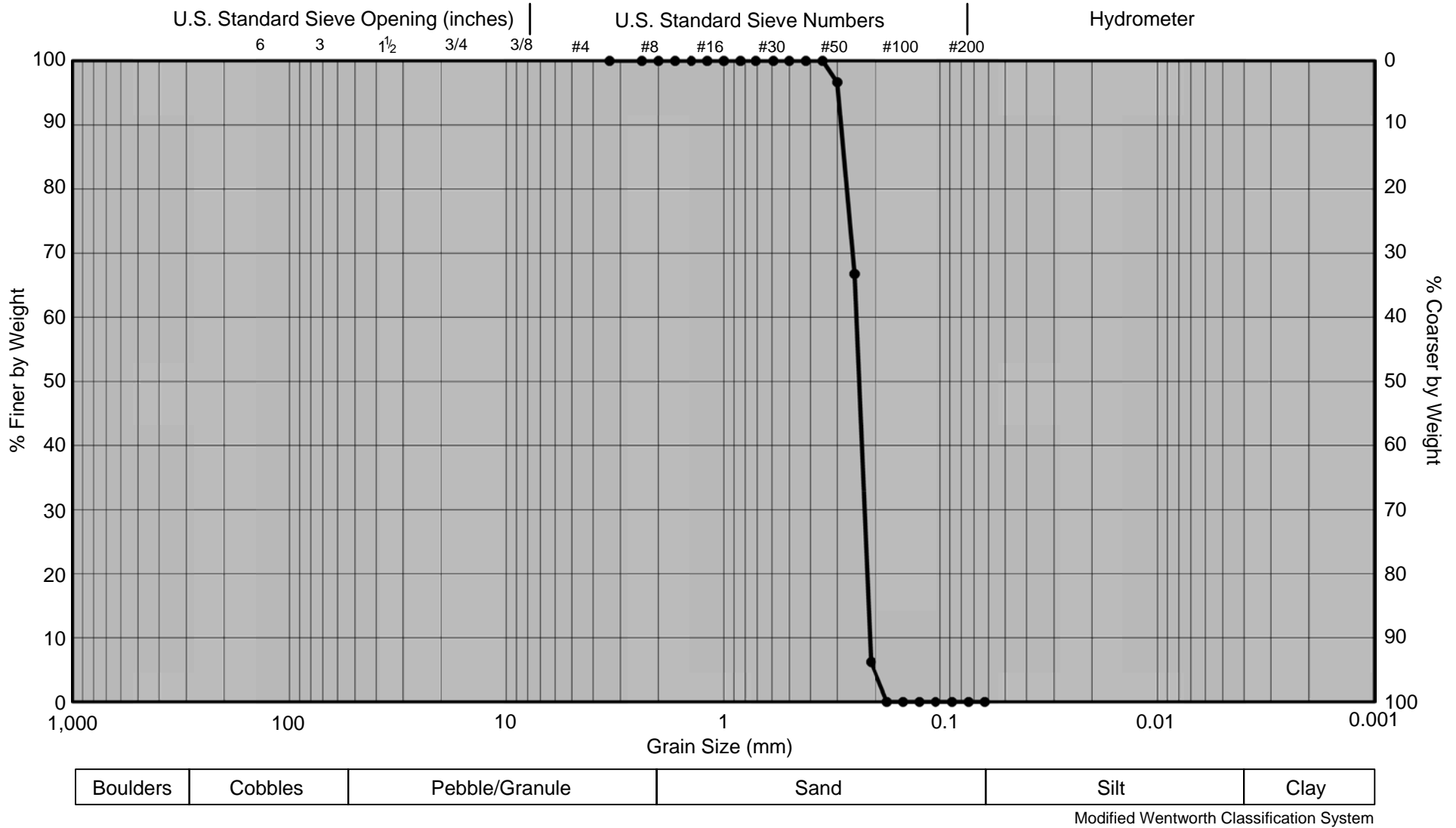


Figure A-III-10. Grain size distribution diagram for Sample No. 10 - Tc 40/70 Cut.

PLATES

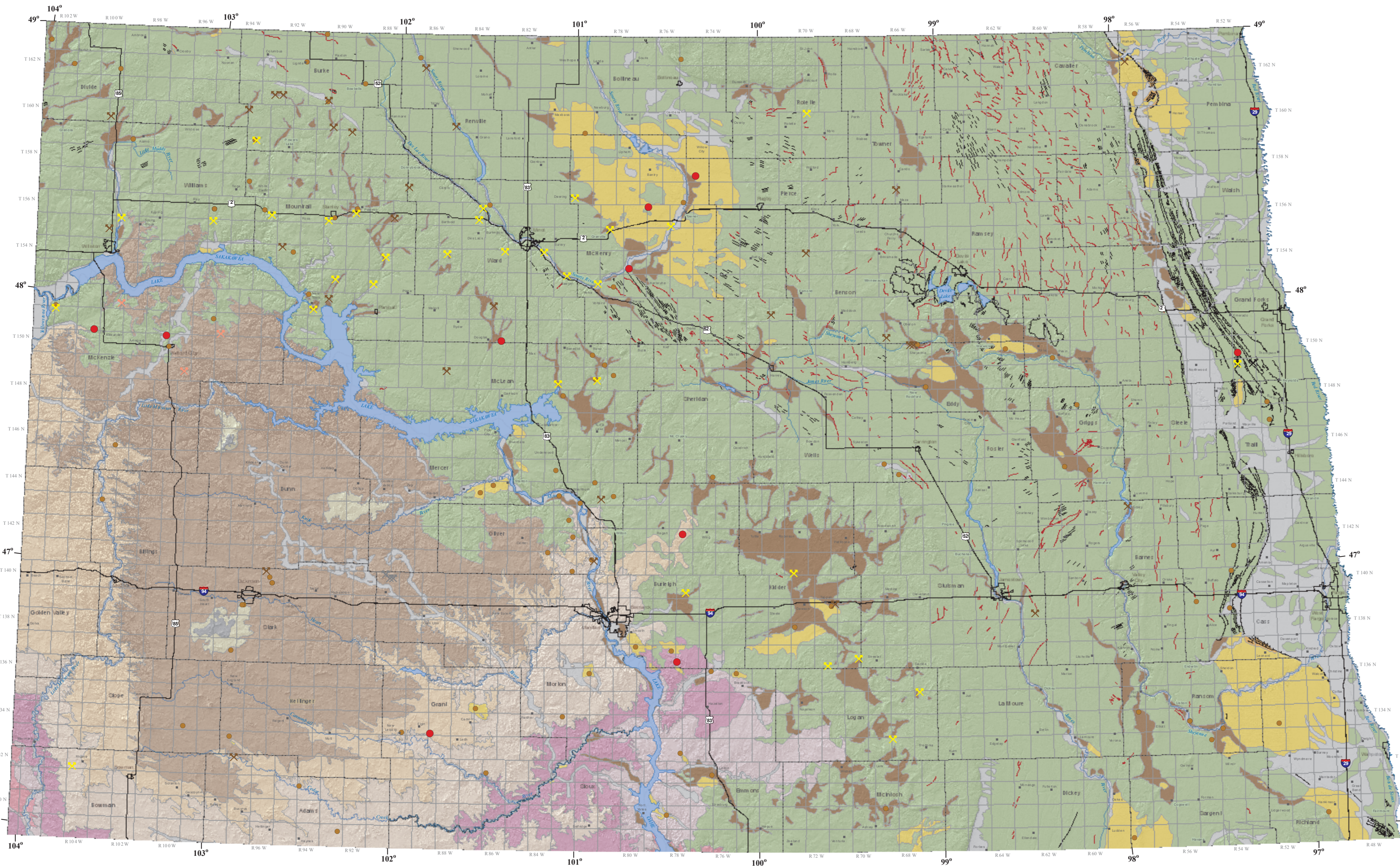
PLATE I – Sand Resources and Sample Locations.

PLATE II – Photomicrograph Examples of Selected Sand Sources in North Dakota.

PLATE III – Field Sand & Gravel Grab Sample Photographic Summary.



Plate I: Sand Resources and Sample Locations



DISCUSSION

Sand (and gravel) resources are found in every county in North Dakota and predominantly consist of glacially derived materials that have been deposited in areas that have been modified by the presence of glacial ice and/or associated meltwaters. Sand resources can also be found in the southwestern part of the state where rocks of Cretaceous and Tertiary age are found and exposed at the surface. Sand deposits in these areas are commonly found as smaller bedded sedimentary units within the larger named formations. The sample locations from this investigation, along with the locations of annual (2010) reported sand and gravel production, are plotted. This is a simplified geologic map, modified from Clayton and others (1980), which depicts geologic units with respect to their sand (and gravel) resource content. Glacial landforms (i.e. eskers, drumlins, and beach ridges) commonly containing localized sand and gravel deposits are also shown.

Table 1. Sand and gravel resources in North Dakota

Geologic Unit	Geologic Age	Approximate Thickness (feet)
Chadron	Quaternary	20-30
Brule	Quaternary	20-30
Golden Valley	Paleocene-Eocene	10-20
Sentinel Butte	Paleocene-Eocene	10-20
Bullion Creek	Paleocene-Eocene	10-20
Ludlow, Cannonball, Slope	Cretaceous	10-20
Hell Creek	Cretaceous	10-20
Fox Hills	Cretaceous	10-20
Pierre	Cretaceous	10-20

EXPLANATION

- ### QUATERNARY
- Fluvial Sand**
Cross-bedded sand; as thick as 30 feet (10 meters); originally deposited on flood plains. Commonly found within channels of modern streams and rivers.
 - Eolian Sand**
Windblown, well sorted, fine grained sand up to 30 feet (10 meters) thick, occurring as dune deposits.
 - Glaciofluvial Sand & Gravel**
Well sorted to moderately well-sorted sand and gravel up to 100 feet (30 meters) in thickness. Commonly found as outwash plains or as terrace deposits along modern streams and rivers.
 - Glaciolacustrine Sand**
Well sorted sand and gravel of beach ridges along the former glacial Lake Agassiz shoreline in the western Red River Valley.
 - Glacial Drift**
Unsorted, unbedded, mixture of sand, silt, clay, with pebbles and occasional boulders (till).

GEOLOGIC SYMBOLS

Locations of Samples Collected During Investigation

- Samples Collected and Tested for Use as Natural Sand Proppant
- Candidate Samples Collected for Potential Testing

2010 Reported Aggregate Production Locations (NDSSCC)

- ✕ Clay
- ✕ Sand/Gravel
- ✕ Gravel
- ✕ Crushed Rock
- ✕ Scoria

Landforms Associated with Sand (and Gravel) Deposits

- Beach Ridges
- Drumlins
- Eskers

Misc Symbols

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

TERTIARY

- #### WHITE RIVER GROUP
- CHADRON and BRULE FORMATIONS (undifferentiated)**
Light colored sand and clay overlain by pinkish siltstone, clay, and sand.
- #### PALEOCENE-EOCENE
- GOLDEN VALLEY FORMATION**
Yellow-brown sandstone, sand, silt, and clay.
 - SENTINEL BUTTE FORMATION**
Gray-brown silt, sand, clay, sandstone, and lignite.
 - BULLION CREEK FORMATION**
Yellow-brown silt, clay, sandstone, and lignite.
 - LUDLOW, CANNONBALL and SLOPE FORMATIONS (undifferentiated)**
Gray-olive-yellow-brown siltstone, shales, and sandstones with lignite.

CRETACEOUS

- HELL CREEK FORMATION**
Gray sand, silt, clay, and sandstone.
- FOX HILLS FORMATION**
Olive-brown sand, shale, and sandstone.
- PIERRE FORMATION**
Dark-gray shale.

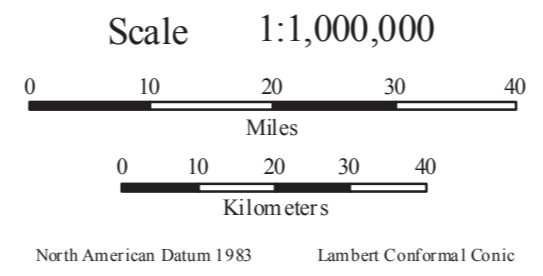
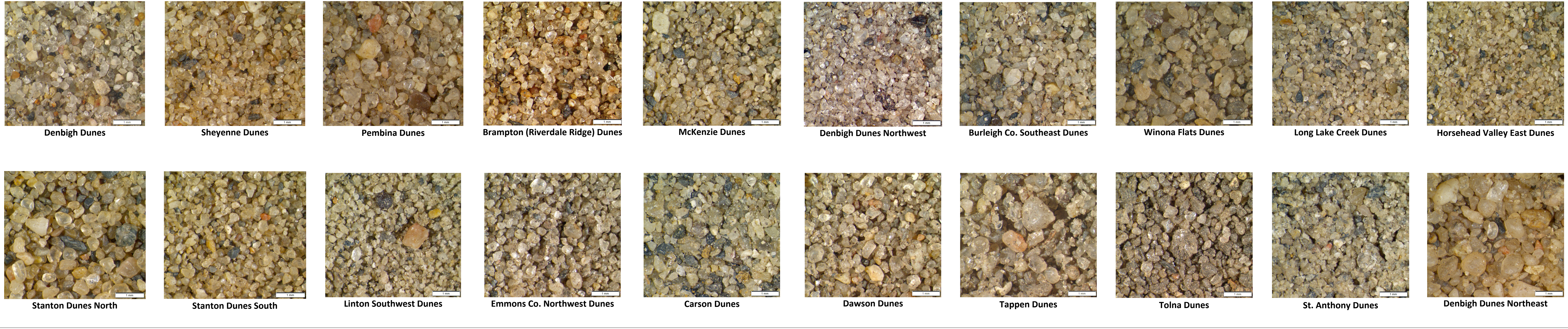
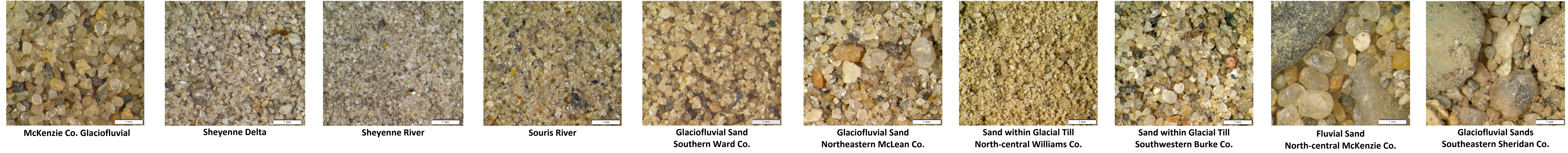


PLATE II. PHOTOMICROGRAPH EXAMPLES OF SELECTED SAND SOURCES IN NORTH DAKOTA

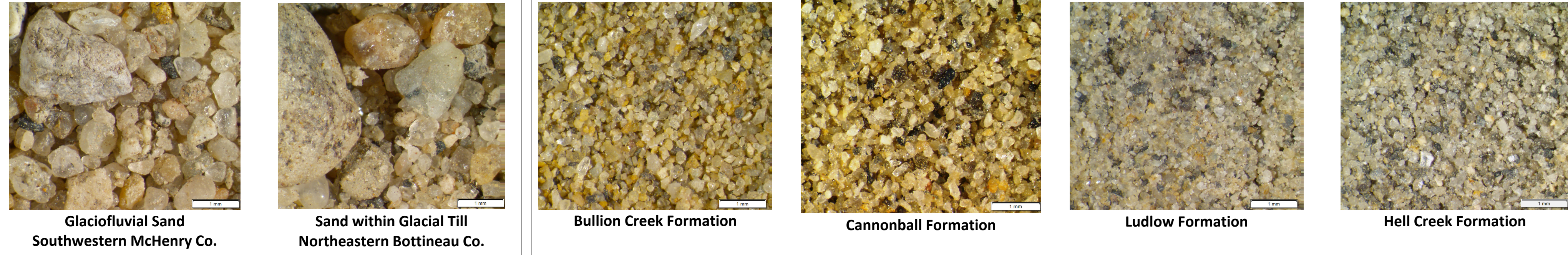
EOLIAN SANDS



GLACIAL-FLUVIAL SANDS



TERTIARY BEDROCK SANDS



PROPPANT SANDS (IMPORTED)



Photomicrographs (25x) of selected sand sources in North Dakota. Eolian (windblown), glacial-fluvial, and sands from Tertiary bedrock formations are included. Selected photomicrographs of proppant sands commonly used in industry are also shown for comparison.

PLATE III. FIELD SAND & GRAVEL GRAB SAMPLE PHOTOGRAPHIC SUMMARY



The samples photographed and displayed in this appendix were collected during opportunity sampling events conducted during geologic field investigations completed during the 2009 summer field season. These photos are included in this report in order to demonstrate the wide variety of sand and gravel deposit types present throughout North Dakota.