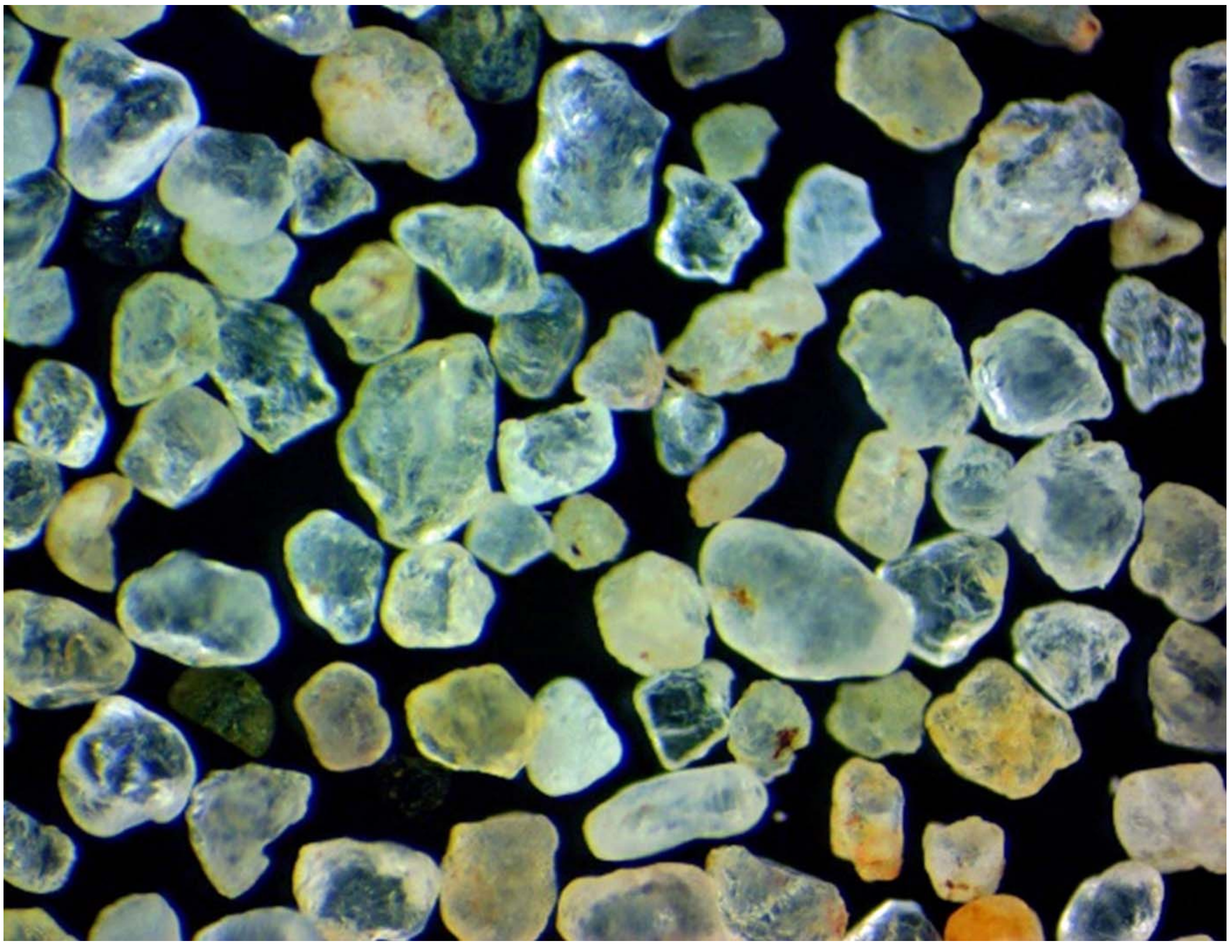
Evaluation of Eolian Sand Deposits in North and South-Central North Dakota for Potential Use as Proppant

Fred J. Anderson



REPORT OF INVESTIGATION NO. 123
NORTH DAKOTA GEOLOGICAL SURVEY
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Abstract

Eolian sand deposits in north and south-central North Dakota were sampled during the summer of 2019. Sand from the Denbigh, Lake Richard, Lincoln, and Carson Dunes was evaluated for use as proppant sand in the hydraulic fracturing of oil and gas wells in the Williston Basin. Testing was performed on five samples from four locations revealing that these windblown sands are dominantly well-sorted, medium to very-fine grained (40/70 & 70/140), with a quartz content ranging from 58 - 82%, and crush resistance K-values ranging from 3,000 to 6,000 psi (3K-6K). Acid solubilities in these eolian sands ranged from 5.3 - 10.5% with turbidity values ranging from 37 - 147 FTU. Loss on ignition testing, as a proxy for detrital lignite content, ranged from 0.31 - 1.44%. Sand grain roundness and sphericity averaged 0.5 and 0.8, respectively. Feldspar contents (microcline and albite) averaged 22% with an average of 5% clays. Average bulk density of these sands is 85.9 pcf. These results indicate that eolian sand deposits in these areas may have potential for use as proppant, ultimately to be determined by industry.

Acknowledgements

The author would like to thank the North Dakota Department of Trust Lands, and each of the private landowners, for access to the eolian sand areas sampled in this report. Proppant sand testing services were provided by Lonquist Field Services, Inc. in College Station, Texas.

Author's Note

Recently the oil and gas industry has relaxed proppant testing specifications in parts of the U.S. in favor of more regional or local sand sources. This evaluation was conducted in response to requests to further investigate the state's sand resources for potential use as proppant in the hydraulic fracturing of oil and gas wells in the Williston Basin. The evaluation and testing performed as a part of this investigation, conform to the recommended practices and standards of the American Petroleum Institute (API) and the International Organization for Standards (ISO).

On the cover: Photomicrograph (40x) of eolian sand (40/70) from the southeastern Denbigh Dunes in McHenry County, North Dakota. Sample No. 1-DBD was collected from an area of rolling sand dunes approximately 16-miles south of Towner, North Dakota.

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INTRODUCTION

Selected samples from four eolian sand deposits in north and south-central North Dakota were collected during the summer of 2019 and submitted to Lonquist Field Services (lab) in College Station, Texas, for proppant testing and characterization. These four samples were collected from the southern Denbigh Dunes in southeastern McHenry County, the Lake Richard Dunes in north-central Sheridan County, the central Lincoln Dunes in southwestern Burleigh County just southeast of Bismarck and Lincoln, and the southeastern Carson Dunes in northeastern Grant County (Table 1, Figure 1). Samples were collected from surface exposures using the methods outlined in Anderson (2011).

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

PREVIOUS WORKS

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

In 2018 it was learned that there was a desire by the oil and gas industry to source their proppant sand from in-basin sources in order to avoid the high costs associated with importing sands from other parts of the U.S., particularly the upper-Midwest, and from overseas. The Survey responded by publishing Geologic Investigation No. 207 (Anderson, 2018) which compiled available geologic information on eolian (wind-blown) sand deposits across the state, including grain size and general composition.

Based on continued feedback from industry about the importance of sourcing sand from deposits in close proximity to the heart of oil and gas activity in the Bakken, additional study was then turned to more fully characterizing the eolian sand deposits near Hazen and Stanton in west-central North Dakota. (Anderson, 2019). It was concluded therein that the sand deposits in the Hazen and Stanton dune fields may be suitable for use as proppant sand. Additional investigation is ongoing in the Hazen-Stanton area, the Denbigh Dunes, as well as across the state.

Table 1. Sample Location Summary

Sample No.	Eolian Sand Area	County	Location (PLSS)	Description	Field Acid Reactivity (10% HCl)
1-DBD	Denbigh Dunes	North & Central McHenry	154-76-36-SE	High Dunes Area, Dune Face Exposure	NR
2-LRD	Lake Richard Dunes	Northcentral Sheridan	150-75-08-SE	High Dunes Area, Dune Form Exposure	NR
3-LND	Lincoln Dunes	Southwest Burleigh	138-79-32-SE	High Dunes Area, Blowout Exposure	NR
4-CRD	Carson Dunes	Northeastern Grant	134-86-09-NW	Low Dunes Area, Dune Dugout Exposure	NR

NR = Non-Reactive.

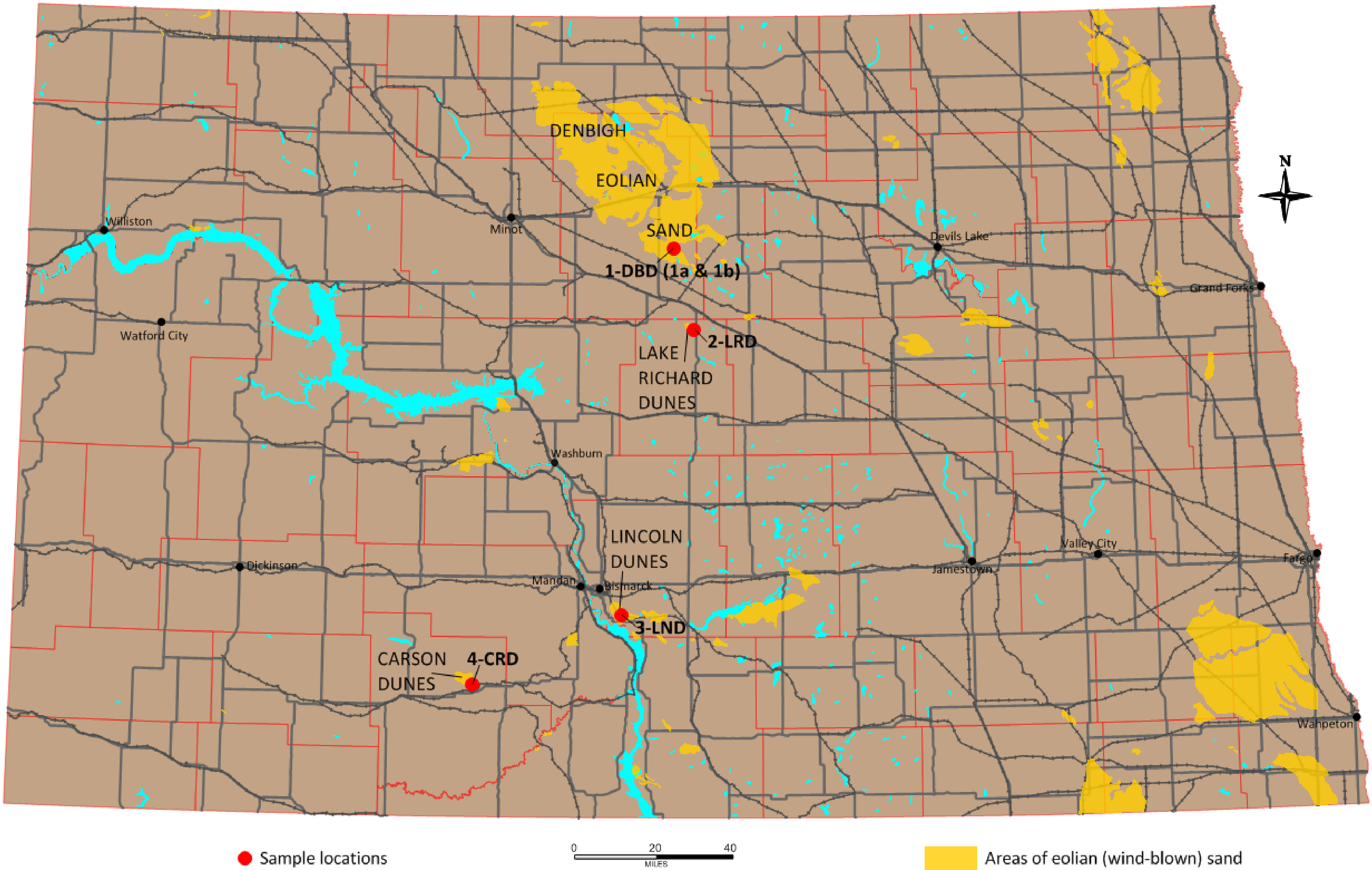


Figure 1. The location of eolian sand samples discussed in this report (Denbigh (1-DBD), Lake Richard (2-LRD), Lincoln (3-LND), and Carson (4-CRD)Dunes), as well as the other major eolian deposits in the state.

EOLIAN SAND DEPOSITS SAMPLED

Denbigh Dunes

The Denbigh Dunes are located roughly 25 miles northwest of Minot and extend across the southern portion of Bottineau County, the northern ¾ of McHenry County (Bluemle, 1982), and the northwestern corner of Pierce County in north-central North Dakota (Figure 1). The Denbigh Dunes cover an area of approximately 1,000 square miles (~28 townships). The sands are distributed in two major settings, 1) as gently rolling tabular sheet sands between areas of low-dunes, with relief of up to 10-feet, and 2) as high-dunes, with relief commonly between 30 to 60-feet. The high-dunes areas encompass approximately 30% of the Denbigh Dunes. All of the eolian sands in this area tend to be under vegetative cover (natural grasses, shrubs, and trees) with only the occasional blowout or dune face exposing the underlying sand (Figure 2). Sample No. 1-DBD was collected from the side of an exposed high-dune in the southeastern portion of the Denbigh Dunes on North Dakota State Trust Lands (NDSTL), just north of Lake George approximately 16 miles south of Towner (154-76-36-SE).

Lake Richard Dunes

The Lake Richard Dunes are located roughly four miles southwest of Anamoose (Bluemle, 1982) and cover one and a half square miles in north-central Sheridan County (Figure 1). Eolian sands in the Lake Richard Dunes are distributed as gently rolling areas of low-dunes with relief of up to 10-feet, with occasional high-dunes. Primarily the majority of the eolian sands in this area tend to be under vegetative cover (natural grasses, shrubs, and trees) with only the occasional dune face exposure permitting a look at the underlying sand (Figure 3). Sample No. 2-LRD was collected from a roadway exposure along the side of an exposed dune in the southeastern part of the dune field (150-75-08-SE).

Lincoln Dunes

The Lincoln Dunes are located immediately southeast of the town of Lincoln (Kume and Hansen, 1965), and extend across a 21- square-mile area in southwestern Burleigh (Figure 1). These dunes, bordered by Lincoln on the north and the Missouri River to the south, are distributed as gently rolling tabular sheet sands between areas of low-dunes and high-dunes, with occasional blowout exposures (Figure 4). Most of the eolian sands in this area tend to be under either vegetative (natural grasses, shrubs, and trees) or agricultural cover with only an occasional blowout or dune face exposing the underlying sand. Sample No. 3-LND was collected from a high-dune blowout exposure in the central part of the dunes area (138-79-32-SE).

Carson Dunes

The Carson Dunes are located two miles northeast of Carson (Carlson, 1982) and cover an area of approximately 16 square miles in northeastern Grant County (Figure 1). Sands in the Carson deposit are distributed as gently rolling low-dunes, with the occasional high-dune. The dunes were deposited in and amongst the erosional remnants of Bullion Creek Formation sandstone in this area.

Figure 2. Aerial oblique drone image (view to the northwest) of the southeastern Denbigh Dunes (154-76-36-SE1/4) in southeastern McHenry county, 11 miles west of Karlsruhe. Vegetation stabilized dunes in this area reach heights of up to 30-feet. Sample 1-DBD was collected from this area.

Figure 3. View to the south on 14th Avenue NE along the eastern edge of the Lake Richard Dunes, 4.5 miles southwest of Anamoose in northcentral Sheridan County (150-75-08-SE1/4). Sample No. 2-LRD was collected from this area.

Figure 4. A vegetated blowout exposure of dune sand from the central Lincoln Dunes in southwestern Burleigh county (138-79-32-SE1/4). View is to the west. Photograph taken just east of the Copper Ridge housing development, southeast of Lincoln. Sample No. 3-LND was collected from this area.

These eolian sands tend to be under either vegetative (natural grasses, shrubs, and trees) or agricultural/grazing ground cover (Figure 5). Sample No. 4-CRD was collected from a low-dune dugout exposure in the southeastern part of the dune field (134-86-09-NW).

FIELD ACID REACTIVITY

Carbonate contents are low to absent within these eolian sand deposits. No reaction to dilute (10%) HCl in the field was observed within any of the samples, which serves as a preliminary indication of the potential carbonate content. Each sample was tested for acid reactivity to dilute (10%) hydrochloric (HCl) using a five-class effervescence assessment (Table 2.)

Table 2. Field acid reactivity summary of eolian sands sampled in this study.

Effervescence class	Observed reaction to dilute HCl	Samples
No reactivity	No reaction observed	1a,1b, 2, 3, 4.
Very slightly reactive	Few bubbles seen	-
Slightly reactive	Bubbles readily seen	-
Strongly reactive	Bubbles quickly form low foam	-
Violently reactive	Thick foam forms immediately	-

Figure 5. The southeastern portion of the Carson Dunes in northeastern Grant county, three miles northwest of Carson (134-86-09-NW1/4). View to the southwest. These vegetation-stabilized, low-relief dunes are commonly up to 10-feet high. Sample 4-CRD was collected from this area.

DESCRIPTON OF TESTING RESULTS

Samples of eolian sand were submitted for testing and characterization in accordance with recommendations and specifications for proppant sand published by the American Petroleum Institute (API) and the International Organization for Standards (ISO). Testing included: particle size distribution (sieve analysis), analysis of grain morphology (sphericity and roundness), acid solubility, turbidity (amount of silt and clay fines), crush resistance, mineralogic evaluation, loss on ignition, and traditional material density testing. Long-term conductivity testing was not performed during this investigation due to lack of overall sand quality and budgetary considerations. Testing and analyses were completed by Lonquist Field Services, Inc., labs located in College Station, Texas during the summer of 2019.

Sample Preparation

All samples submitted for testing were prepared for analysis by washing on the #200 sieve, drying, and disassociation (Table 3). Gradational analysis was first performed on prepared samples to determine the dominant sand size fractions. Remaining tests were then performed on the dominant sand size fraction, in this case sands falling within either the 40/70 or 70/140 size classification (Table 4). Qualitative and quantitative XRD mineralogy was performed on prepared sand samples in order to provide a more accurate assessment of sand mineralogy.

Particle Size Distribution – Textural (Sieve) Analysis

Sieve analyses are conducted on sediment samples in order to quantify the different sized sand grains within an individual sample. A series of stacked, wire-mesh sieves of standard sizes was used to sieve each sand sample. Amounts of sand either being retained by the screen on each successively smaller opening sized sieve (% retained) or passing through the screen (% passing) is recorded and reported commonly as tabular data (Table 5) or in graphical form on a grain-size distribution diagram (Figure 6).

The resulting graph and grain-size curves depict the volume on the amounts of particle sizes present and the degree of sorting or the variability (or lack thereof) of grains sizes. A well-sorted sample (poorly graded in engineering terms), will have much of the sample volume within or near the same size classes (Table 5), resulting in a very steep curve on the grain size distribution diagram (Figure 6). All of the samples selected for testing were well sorted (poorly graded) sands falling into the medium to very-fine grained size classes.

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

Table 3. Wash Loss on Bulk Sample

Sample No.	Wash Loss (%)	Over-Size Waste (%)	Fines Waste (%)	Sample Total	
				Waste	Product[1]
1-DBD	2.06	16.9	0.9	19.9	80.1
2-LRD	14.57	19.2	4.6	38.4	60.2
3-LND	15.28	15.1	2.0	32.3	67.7
4-CRD	26.15	0.2	3.2	29.7	70.3

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

Table 4. Proppant Testing Analytical Summary of Selected Eolian Sands in north and south-central North Dakota.

Sample No.	Tested Size Class	Quartz Content (%)	Crush Resistance (K-Value)	Acid Solubility (%)	Shape Factors		ISO Mean Particle Dia. (mm)	Median Particle Dia. (mm)	Turbidity (FTU)	Loss on Ignition (%)	Bulk Density (pcf)	Absolute Density (g/cm^3)
					Roundness	Sphericity						
1a-DBD	40/70	79.2	5K	5.3	0.5	0.8	0.320	0.293	37.3	0.31	89.0	1.59
1b-DBD	70/140	81.8	6K	7.7	0.5	0.8	0.320	0.293	67.2	0.41	86.7	1.53
2-LRD	70/140	79.5	4K	10.5	0.5	0.8	0.441	0.269	96	1.44	86.0	1.48
3-LND	70/140	75.2	5K	7.6	0.4	0.8	0.299	0.252	147	0.71	85.8	1.47
4-CRD	70/140	57.9	3K	10.3	0.4	0.7	0.233	0.202	45	1.30	81.9	1.41

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

FTU = Formazin Turbidity Unit.

pcf = pounds per cubic foot.

Table 5. Bulk Sample Sieve Analysis Results Summary (Weight % Retained)

Sample No.		1-DBD	2-LRD	3-LND	4-CRD
Sieve No.	6	0.0	1.6	0.0	0.0
	8	0.0	1.0	0.0	0.7
	16	0.0	3.9	0.0	0.3
	30	2.4	7.9	3.7	0.2
	40	14.9	9.6	14.0	0.5
	45	13.8	7.6	9.8	1.8
	50	16.5	9.9	10.1	6.2
	60	18.5	14.2	13.0	14.2
	70	11.7	11.2	11.7	19.7
	80	8.9	9.5	12.2	22.0
	100	6.3	7.8	11.0	17.9
	120	4.2	6.4	8.2	9.7
	140	1.9	3.9	4.0	3.7
	170	0.6	2.4	1.4	1.5
	200	0.3	2.1	0.8	1.3
	Pan	0.0	0.9	0.1	0.3
Total		100.0	100.0	100.0	100.0

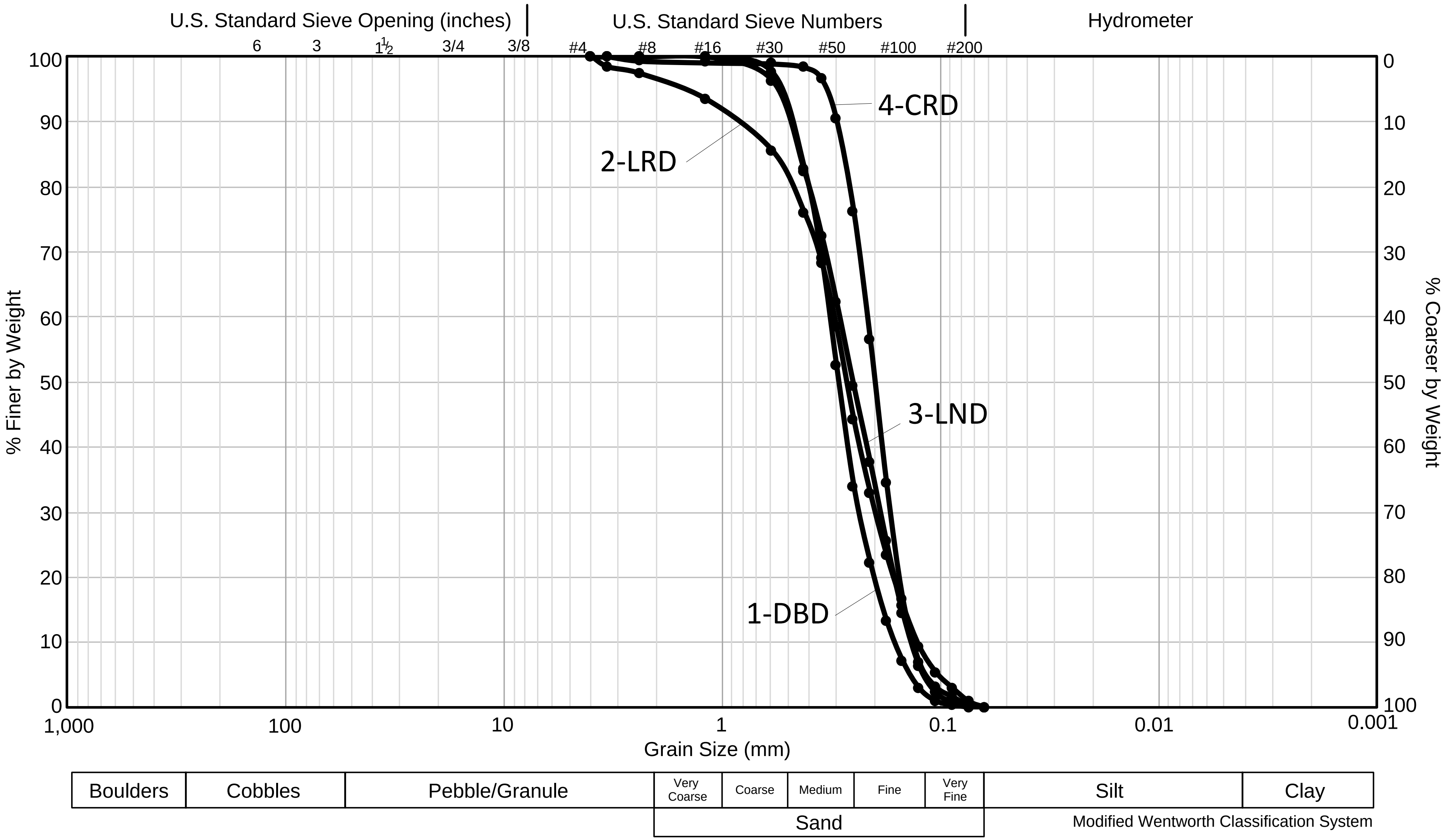


Figure 6. Grain-size distribution curves (sieve analyses) for sand samples from eolian deposits in north- and south-central North Dakota. These sands are well sorted and medium to very-fine grained according to the Modified Wentworth Classification System.

All of the tested samples fall into the grain size ranges for classification as a "sand" according to the Modified Wentworth classification scheme (Figure 6) and can be further characterized as well sorted (poorly graded) to very well sorted, medium- to very-fine grained sands. All of the samples had the majority of grains fall in the 40/70 or 70/140 or "100 mesh" sand size ranges (Table 6).

Statistical analyses can be performed on data generated in a grain-size distribution diagram and used to quantitatively compare individual samples for potential engineering applications. The mean grain-size diameter is commonly used to characterize proppant distribution in hydraulic fracturing applications while the median grain-size diameter is used to characterize gravel-packing distributions (Table 4).

Sand Grain Morphology (Sphericity and Roundness)

Individual sand grain sphericity and roundness are two particle shape factors that are evaluated when characterizing the proppant potential of a sand. These factors can be qualitatively observed through standard photomicrographs (Plates I - III). Sphericity refers to how closely a particular grain of sand resembles that of a sphere and roundness refers to the corners of an individual sand grain. A sand with high sphericity and roundness is desirable for proppant use. The recommended sphericity and roundness values are 0.6 or greater, with values of 0.7 or greater characteristic of high-strength proppants (API, 2018). All four of the samples tested had sphericity values greater than 0.7 and were commonly at 0.8. Roundness values of 0.5 were reported on the sands from the Denbigh and Lake Richard dunes and roundness values of 0.4 were reported from the sands from the Lincoln and Carson dunes (Figure 7). These values approach desired specifications, particularly for sphericity factors, but remain somewhat angular on the roundness scale.

Acid Solubility

The volume of a sand that is soluble in strong acid is an important test of an effective proppant as acid treatments of oil and gas wells are common during completions. API (2018) recommends for proppant sands that no greater than ≤3% (by weight) of 70/140 be soluble in a 12:3 hydrochloric (HCL) or hydrofluoric (HF) acid solution. None of the samples tested were at or below the recommended acid solubility threshold (Figure 8), but are considerably lower than other sand sources tested in North Dakota (Anderson and others, 2019). Acid solubility on these eolian sands ranged from 5.3 to 10.5% (Table 4).

Silt and Clay Fines Testing (Turbidity)

Turbidity tests measure the optical properties of water samples containing suspended sediment and are commonly used to determine the percentage of fine materials (e.g. silts and clays) present. With respect to proppant potential, the turbidity test measures the amount of associated fines within a particular sand sample. It can be used to identify sand sources that require additional washings, etc., during initial processing of raw product into frac-sand. Turbidity is measured and commonly reported in Formazin Turbidity Units (FTU). The recommended limit of frac sand is less than 250 FTU. All of these eolian samples were below the recommended limit of 250 FTU (Figure 9). The samples ranged from 37

Table 6. Percentage of Sand by Size Class

Sample No.		1-DBD	2-LRD	3-LND	4-CRD
Size Class	30/50	44.2	23.1	28.7	6.4
	40/70	59.3	36.7	37.7	31.0
	70/140	20.8	23.6	29.9	39.4
	50/140	50.5	45.3	50.8	64.4

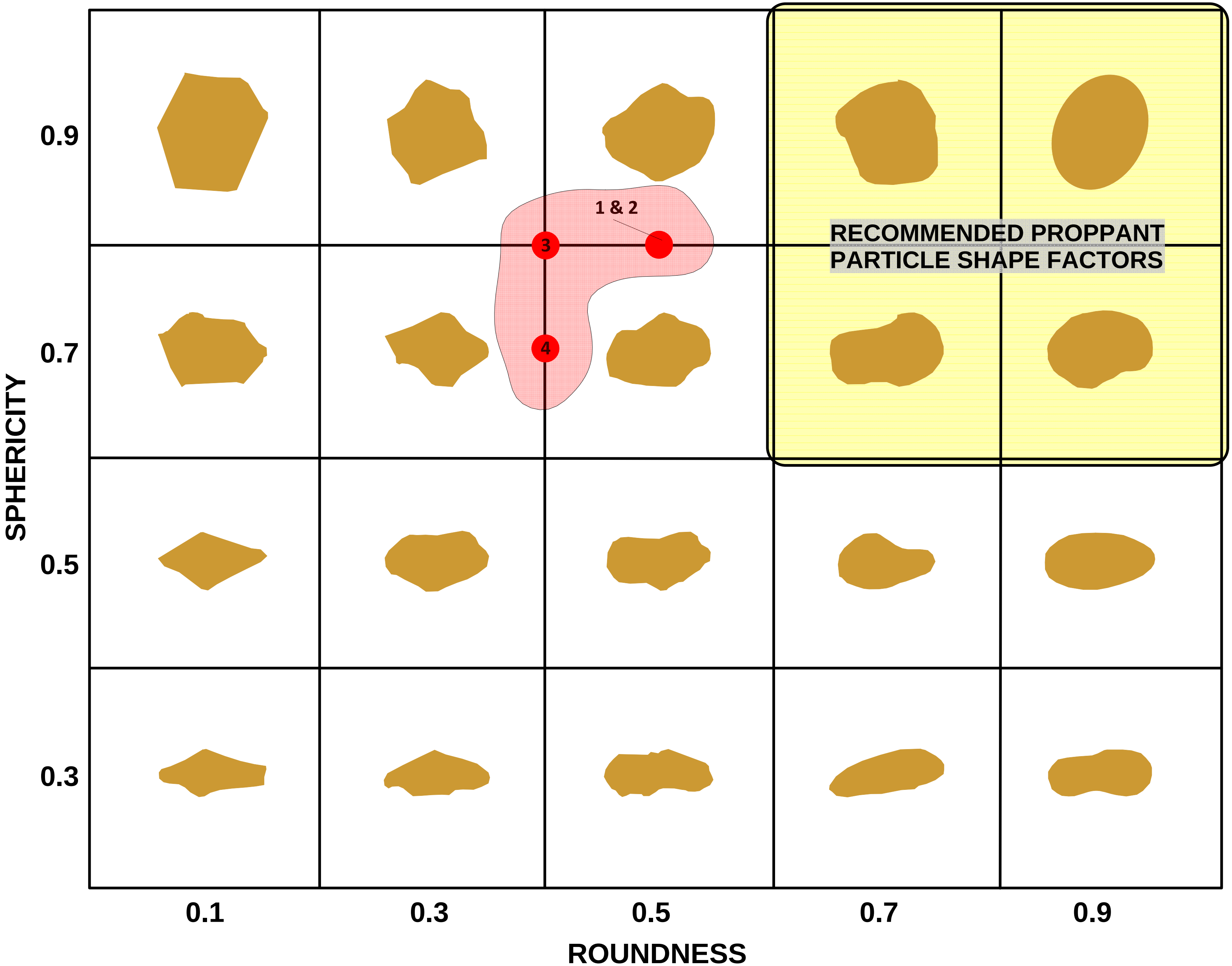


Figure 7. Comparison of sphericity and roundness values for eolian sand samples from the Denbigh Dunes (1), Lake Richard Dunes (2), Lincoln Dunes (3), and Carson Dunes (4) located in north- and south-central North Dakota. Samples from these deposits have particle shape factors that begin to approach the desired specifications (shaded red) for frac sand as compared to "Ottawa White" silica sands.

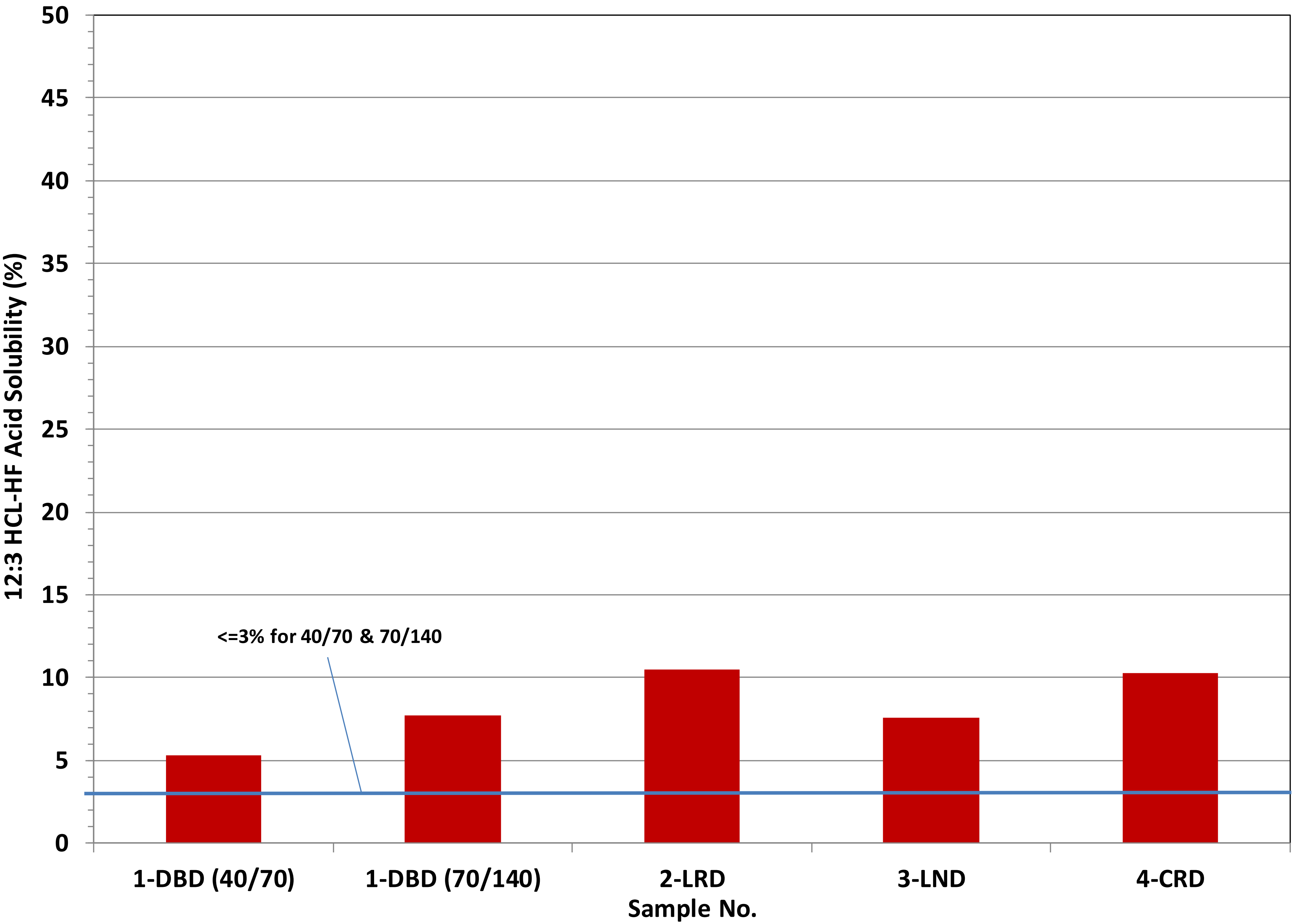


Figure 8. Comparison of hydrochloric:hydrofluoric acid solubility results for eolian sand samples from the Denbigh Dunes (1-DBD 40/70 & 70/140), Lake Richard Dunes (2-LRD), Lincoln Dunes (3-LND), and Carson Dunes (4-CRD). Recommended specifications for acid solubility on 70/140 sands are less than or equal to 3%.

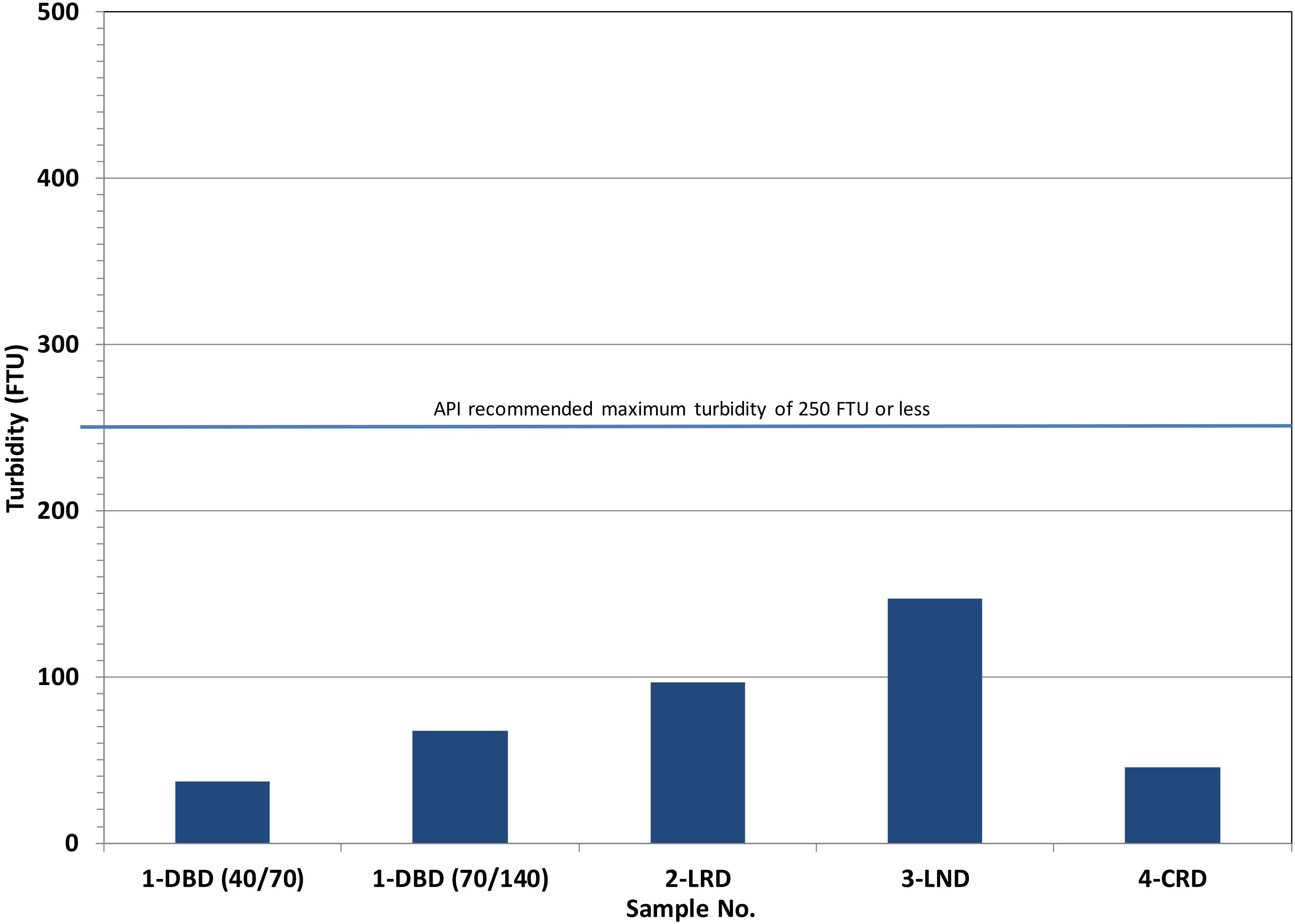


Figure 9. Comparison of turbidity results for eolian sand samples from the Denbigh Dunes (1-DBD 40/70 & 70/140), Lake Richard Dunes (2-LRD), Lincoln Dunes (3-LND), and Carson Dunes (4-CRD). Recommended specifications for turbidity are 250 FTU or less.

FTU in the Denbigh Dunes in McHenry County to 147 FTU from eolian sand from the Lincoln Dunes in southwestern Burleigh County (Table 4).

Crush Resistance

Sand compositions can be quite variable as can the resultant strength. A crush resistance test measures the amount of fine-grained material generated during the subjection of a given sand sample (within a specified size range) to a pre-determined amount of stress or load. Crush resistance testing was performed on all four sand samples. Additionally, the two largest size fractions (40/70 & 70/140) from the Denbigh Dunes were also tested (Figure 10). K-Values were determined by subjecting the samples to one set of two pre-determined stresses, that were determined by the size range of the samples. A K-value is defined as the highest stress level that will generate no more than 10% crushed material (rounded down to the nearest 1,000 psi).

Sample Nos. 1a & 1b from the Denbigh Dunes, were subjected to a stress level set of 5,000, 6,000, and 7,000 psi and generated K-values of 5K and 6K, respectively. Sample No. 2 was subjected to a stress level set of 4,000 and 5,000 psi which generated a K-value of 4K (Table 7). Sample No. 3 from the Lincoln Dunes returned a K-value of 5K. The samples from the Carson Dunes returned a K-Value of 3K. Ottawa "white" sands typically generate K-values between 7 to 15K. Bakken oil and gas wells have fracture closure stresses in the reservoir that range typically around 9,500 psi.

Loss on Ignition Testing

Loss on Ignition (LOI) testing was performed on selected sample size cuts in order to serve as a proxy for determination of the potential detrital lignite content. The LOI values were comparatively low, which is to be expected from a washed sized sample cut, ranging from 0.31% to 1.44%. the LOI values were lowest in the eolian sands from the southeastern portion of the Denbigh Dunes (Figure 11).

Mineralogy (X-Ray Diffraction)

Sample geochemistry was determined using qualitative and quantitative X-ray diffraction (XRD) on all four eolian sand samples (Figure 12). XRD analysis is commonly used to determine the mineralogy of fine-grained lithologies, particularly clays. In general, the samples had similar mineralogical compositions (Table 8) with some variability in the lower percentages of feldspars and clays (Figure 13). Quartz percentages ranged from 58 to 80%, feldspar ranged from 17 to 32%, and clay contents ranged from 3 to 10%. In comparison, Ottawa "white" silica sands are commonly 99% quartz.

Bulk Density

In regard to proppants, the bulk density describes the mass that fills a unit volume and includes both the proppant and the void space (i.e. porosity) in the sample. It is commonly used in determining the mass of proppants required to fill fractures, a storage vessel, or in completing general volume estimates. The bulk density of these eolian sands (Table 4) ranged from 82 to 89 pounds per cubic foot (pcf).

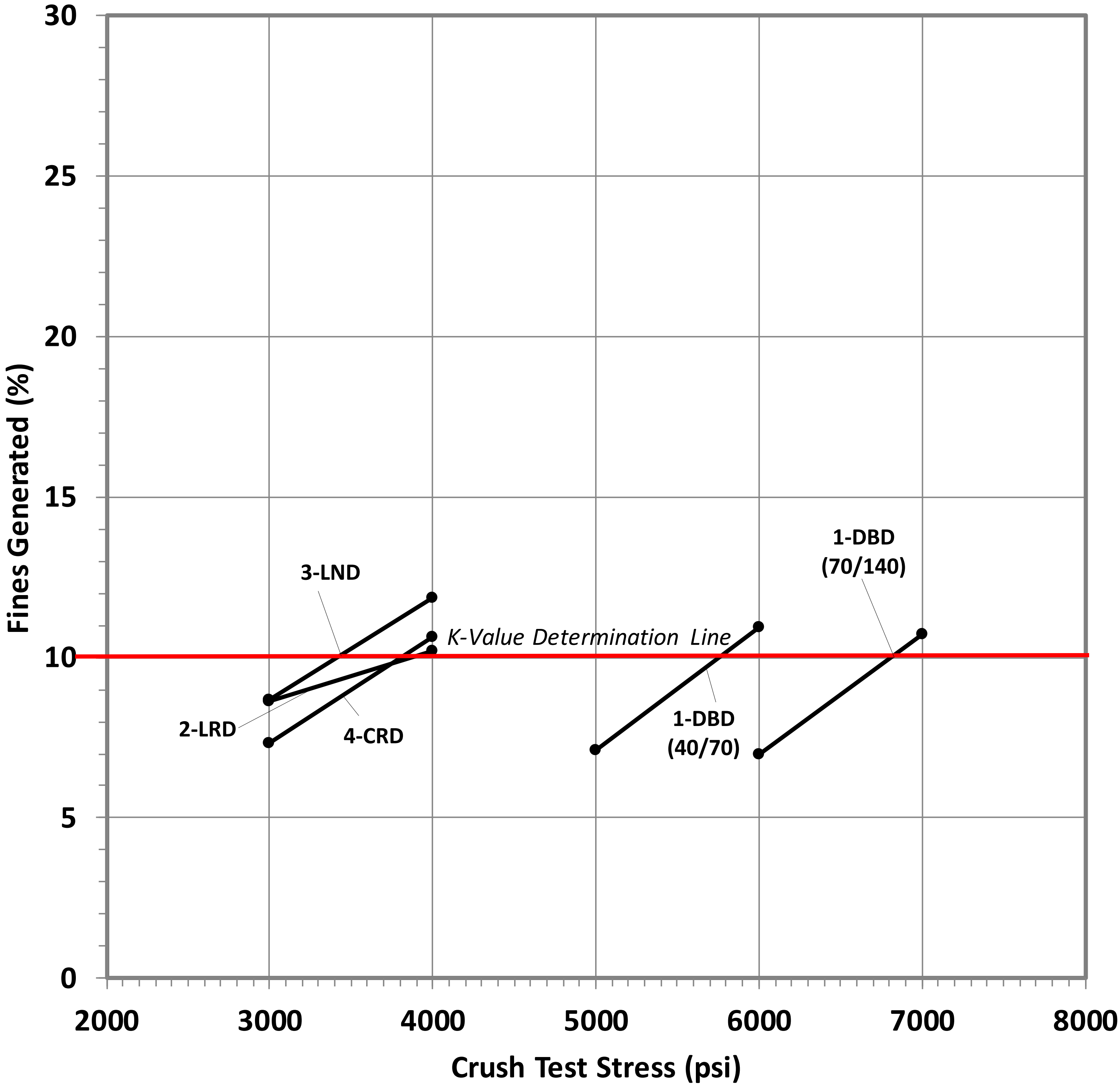


Figure 10. Comparison of crush resistance results for eolian sand samples from the Denbigh Dunes (1-DBD 40/70 & 70/140), Lake Richard Dunes (2-LRD), Lincoln Dunes (3-LND), and Carson Dunes (4-CRD). Recommended specifications for crush resistance for the Bakken are in the range of 8K to 9K (8,000 to 9,000 psi).

Table 7. Crush Resistance Testing Data Summary

Sample No.	**1a-DBD**	**1b-DBD**	**2-LRD**	**3-LND**	**4-CRD**
Size Class	40/70	70/140	70/140	70/140	70/140
Test Stress (psi)	**% Fines Generated**				
3000	--	--	--	--	7.33
4000	--	--	8.63	--	10.62
5000	7.10	--	10.22	8.66	--
6000	10.94	6.98	--	11.85	--
7000	--	10.70	--	--	--
K-Value	5K	6K	4K	5K	3K

-- Stress point not tested.

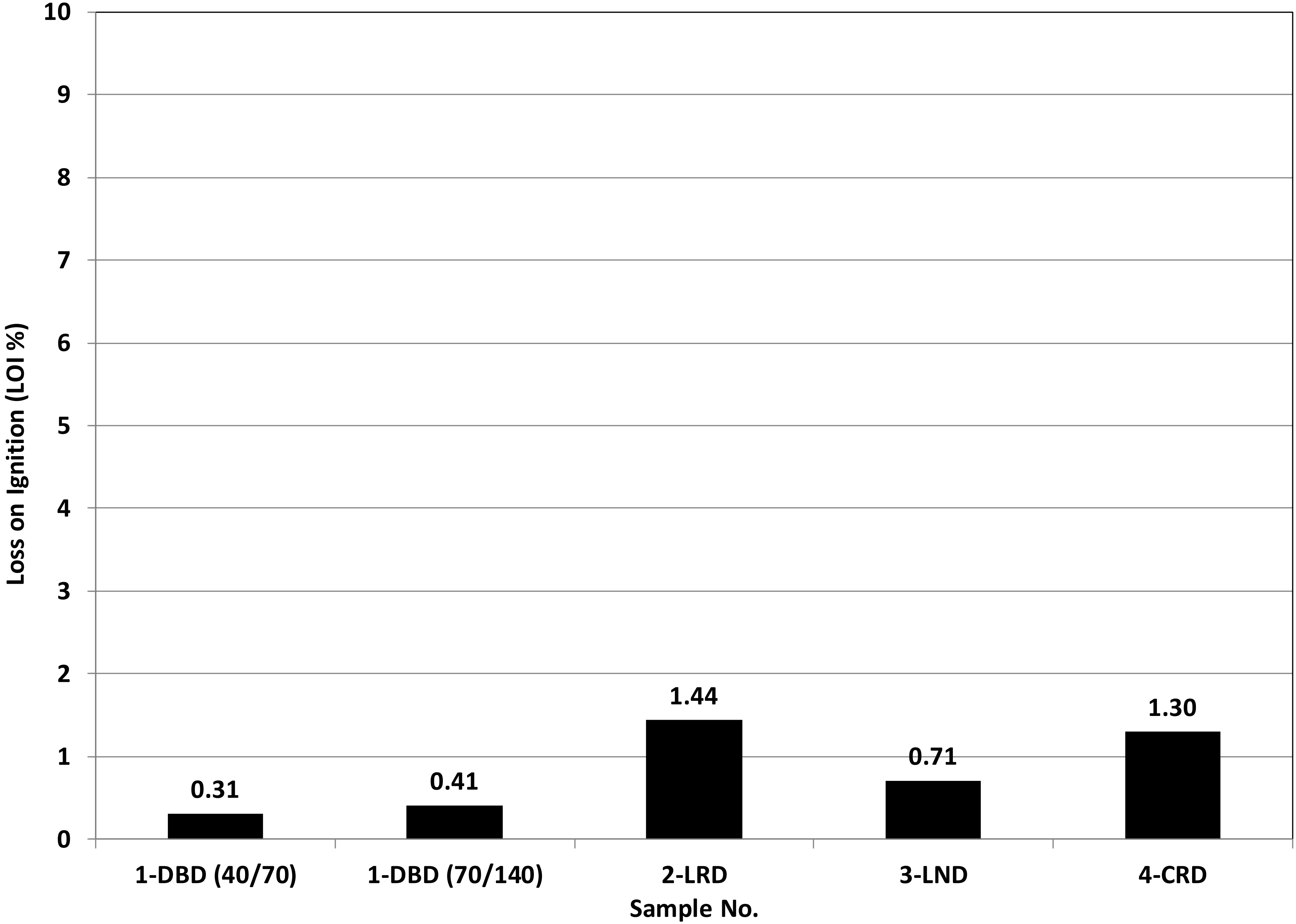


Figure 11. Comparison of loss on ignition (LOI) values as a proxy for detrital lignite content for eolian sand samples from the Denbigh Dunes (1-DBD 40/70 & 1-DBD 70/140), Lake Richard Dunes (2-LRD 70/140), Lincoln Dunes (3-LND 70/140), and Carson Dunes (4-CRD 70/140).

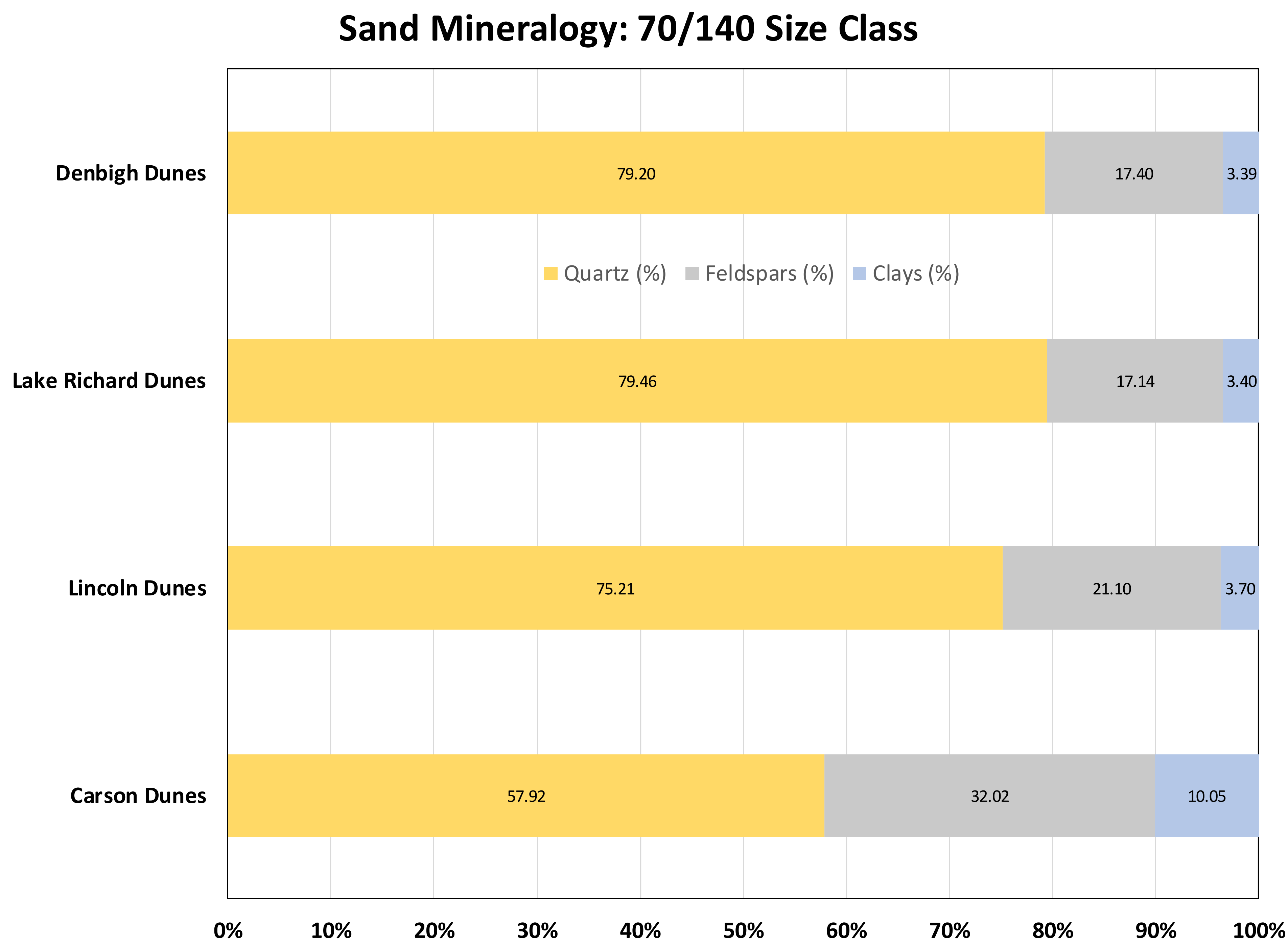
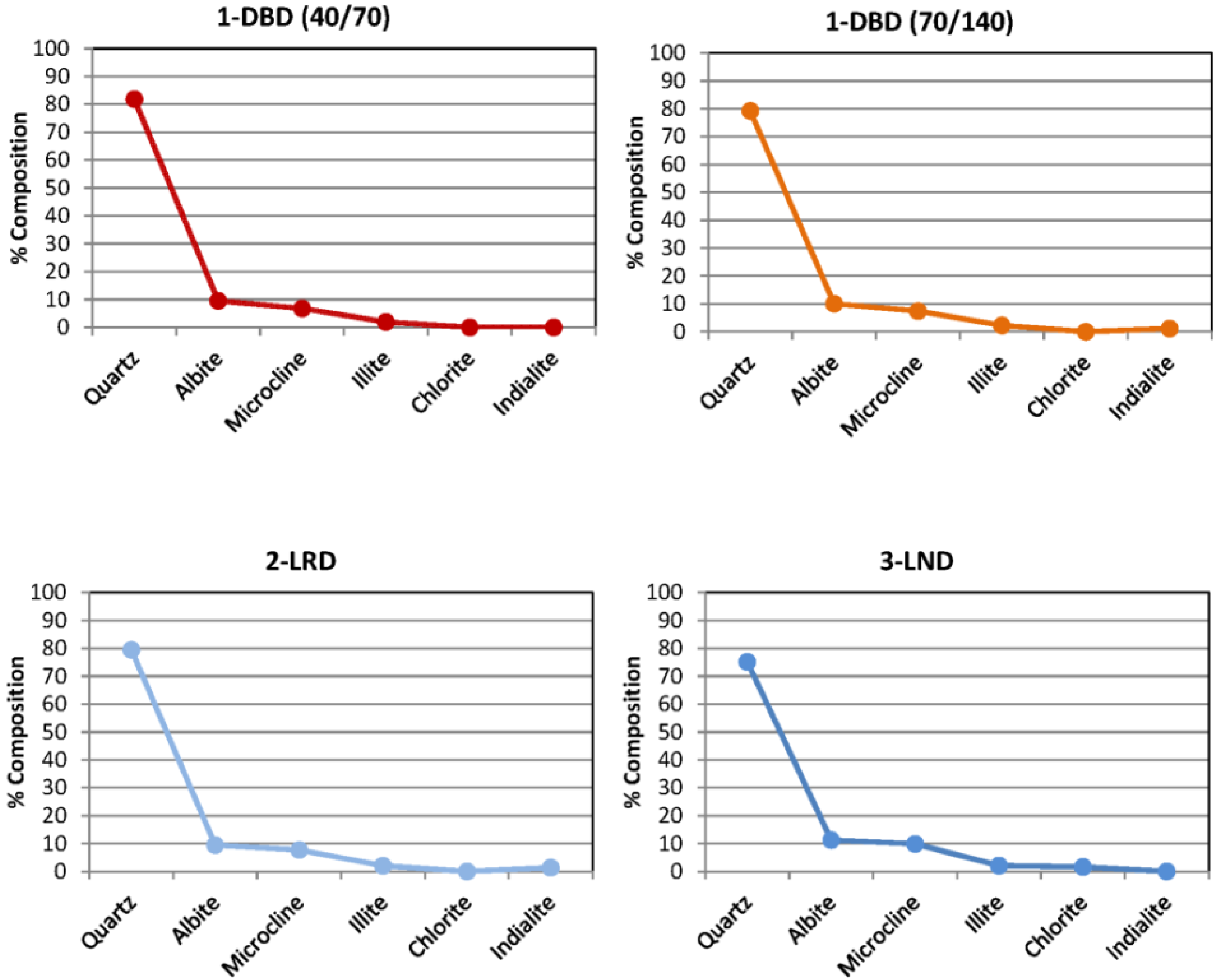


Figure 12. Summary mineralogy of 70/140 sand fraction from selected eolian deposits in north and south-central North Dakota.

Table 8. Sample Mineralogic Composition Summary

Sample No.	Quartz	Albite	Microcline	Illite	Chlorite	Indialite
1-DBD (40/70)	81.82	9.52	6.77	1.89	--	0.00
1-DBD (70/140)	79.20	10.04	7.36	2.26	--	1.13
2-LRD	79.46	9.46	7.68	2.03	--	1.37
3-LND	75.21	11.24	9.86	2.11	1.59	--
4-CRD	57.92	21.17	10.85	4.89	4.01	1.15

-- Not Detected



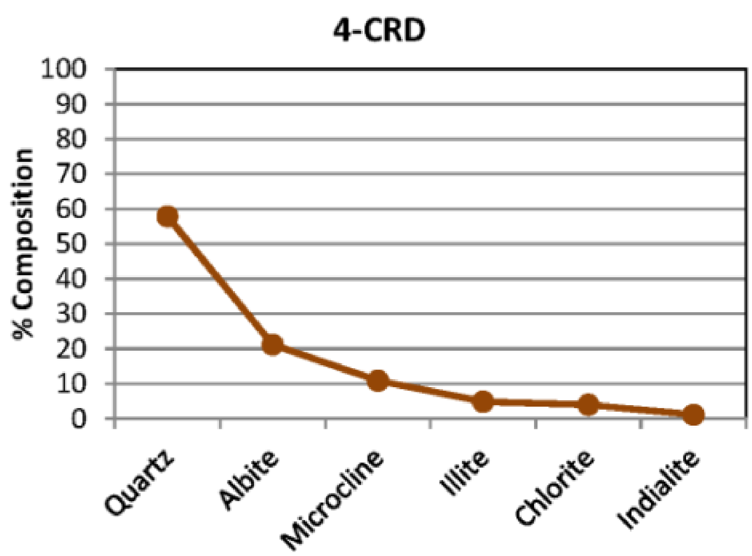


Figure 13. Comparison of X-ray diffraction results for eolian sand samples from the Denbigh Dunes (1-DBD), Lake Richard Dunes (2-LRD), Lincoln Dunes (3-LND), and Carson Dunes (4-CRD). Mineralogic constituents reported include Quartz, Feldspars (Albite & Microcline), and Clays (Illite, Chlorite, and Indialite).

Absolute (particle) density

The absolute density or particle density of a sand measures the density by way of pycnometric (gas displacement) methods. The absolute density of the tested eolian sands, ranged from 1.41 to 1.59 grams per cubic centimeter (g/cm^3) with an average of 1.50 g/cm^3 (Table 4).

CONCLUSIONS

Eolian sand deposits in north and south-central North Dakota have favorable grain size ranges in the smaller grain sizes (40/70 & 70/140), and contain quartz contents that are generally above 75% on washed material. Those factors could be favorable to industry for potential use as proppant sand. However, crush-resistance testing results ranged from 3K to 6K, much lower than the desired values of 9K to 11K for the Bakken system. Particle shape factors continue to approach desired industry specifications for sand grain sphericity and roundness in these deposits. Additional material processing steps may be needed to increase favorable testing results for these sands and will continue to be evaluated. The testing data included in this report should prove valuable for other potential industrial sand uses and future sedimentological research. Additional samples have been collected and are currently being tested. Because of the interest that our previous proppant potential reports have generated, this report has been published ahead of these additional results which should be completed by the end of 2019.

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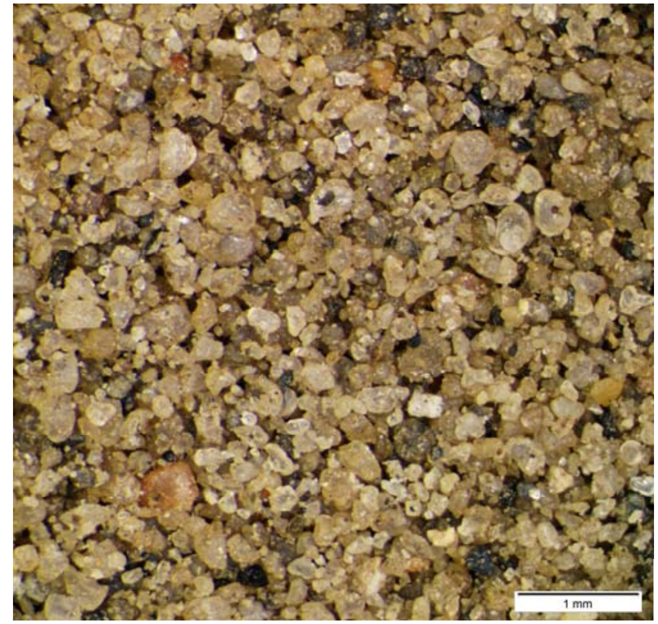
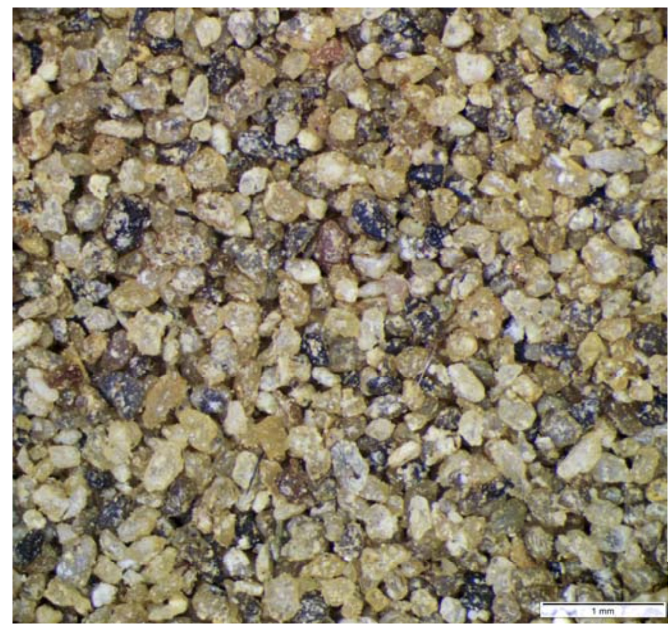
Plate I. Photomicrographs (25x) of bulk eolian sand from the a.) Denbigh Dunes, b.) Lake Richard Dunes, c.) Lincoln Dunes, and d.) Carson Dunes.

a.



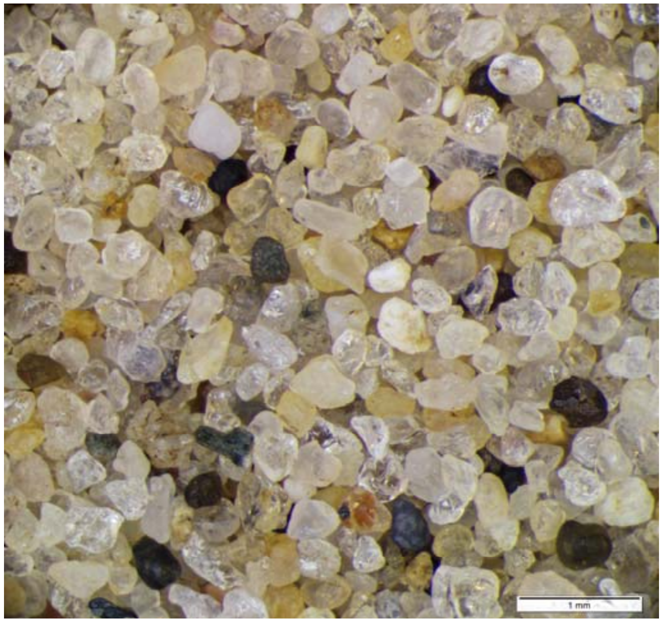
b.

c.



d.

Plate II. Photomicrographs of eolian sand from the Denbigh Dunes: Sample 1a-DBD (40/70) & 1b-DBD (70/140), a.) 40/70 (25x), b.) 40/70 (40x), c.) 70/140 (25x), and d.) 70/140 (40x).



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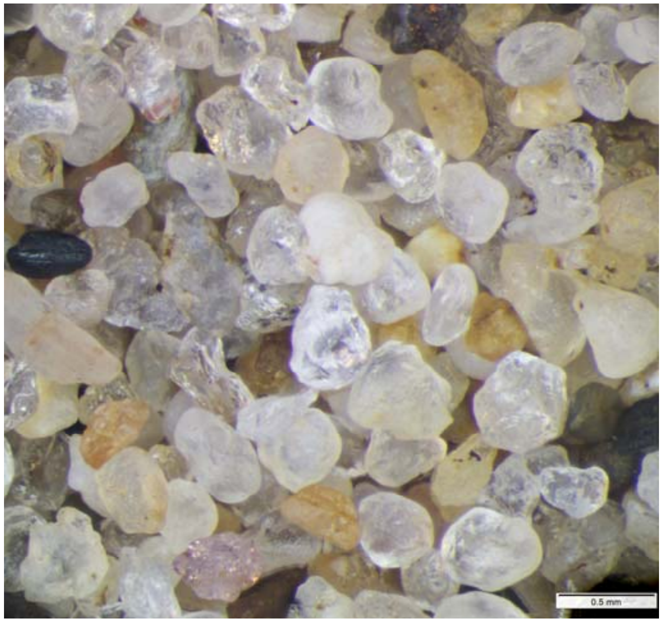

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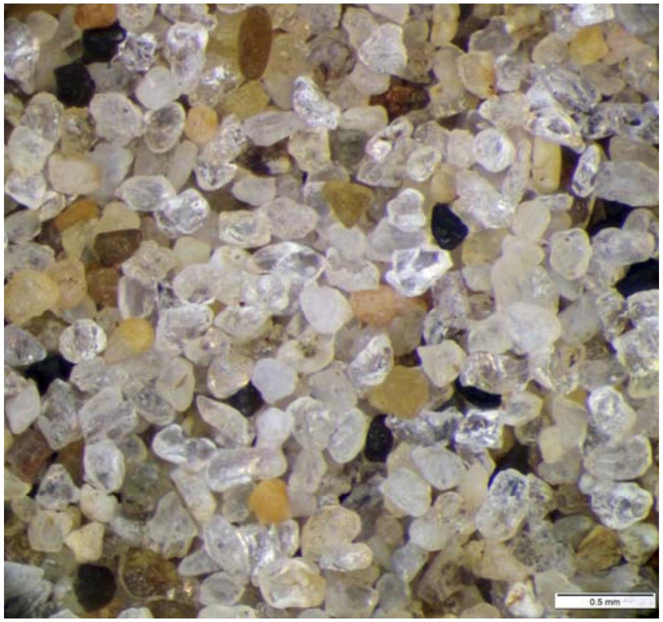

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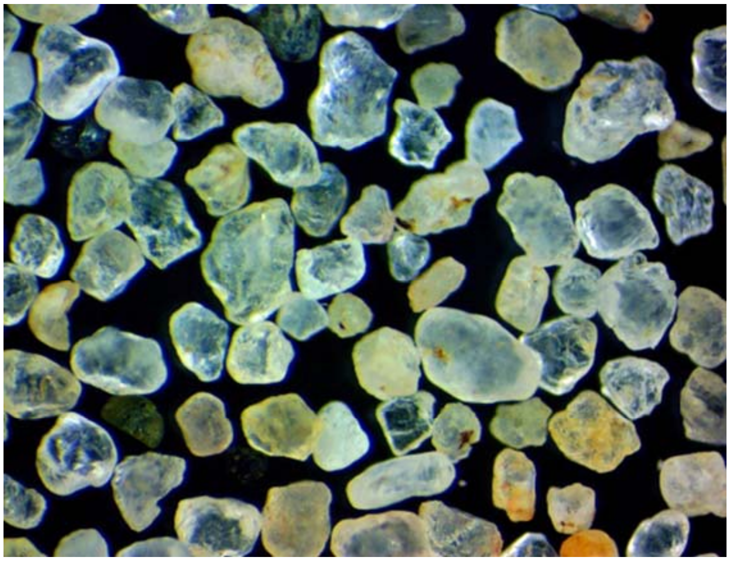

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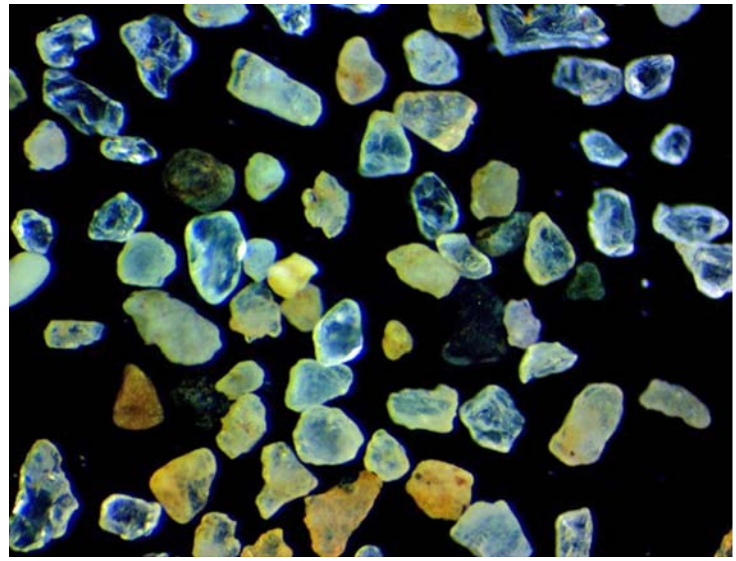

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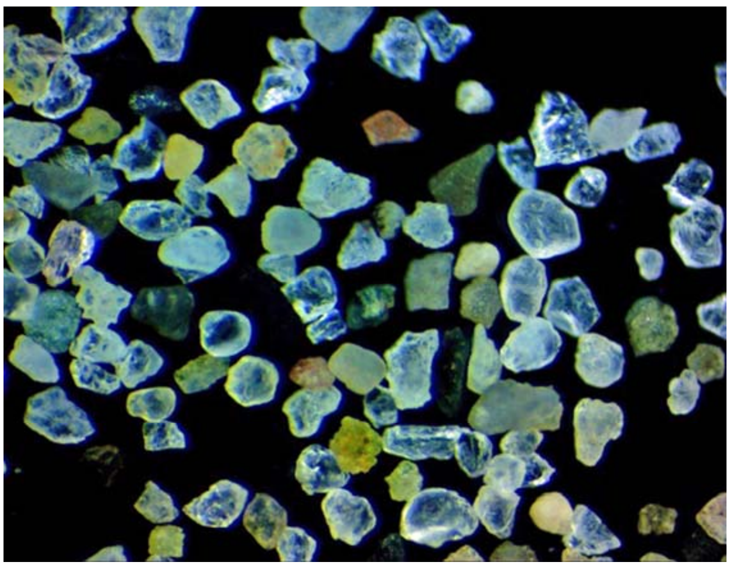
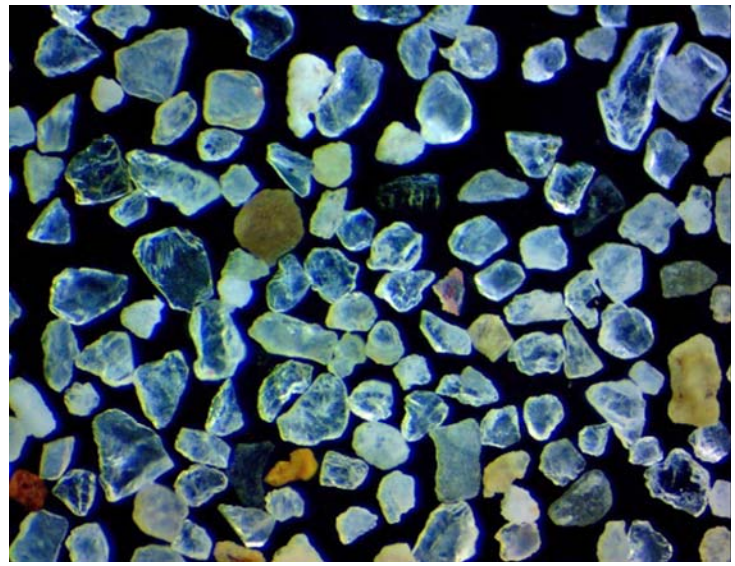
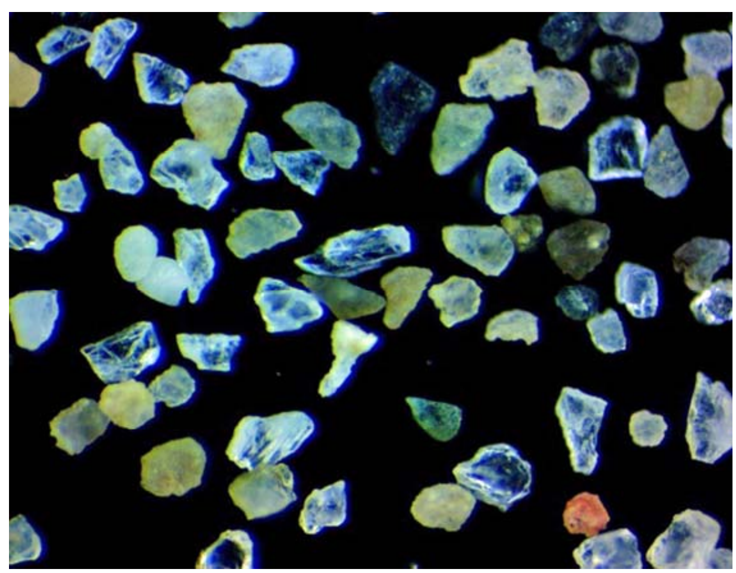


c.



d.

Plate III. Monolayer photomicrographs (40x) of eolian sand from the a. Denbigh Dunes Sample 1a-DBD (40/70) & b. 1b-DBD (70/140), c. the Lake Richard Dunes (2-LRD), d. the Lincoln Dunes (3-LND), and the e. Carson Dunes (4-CRD).



e.