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OIL AND GAS INVESTIGATION 5

ASSESSMENT OF SOUTH DAKOTA'S SAND AND ALUMINA RESOURCES FOR USE AS PROPPANT

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ABSTRACT

Current high demand for proppant in the United States prompted an investigation into potential proppant resources in western South Dakota. The purpose of this study was to characterize selected sand-bearing formations for potential use as natural proppant, and determine if there are any raw materials in South Dakota suitable for the manufacturing of ceramic proppants. The ideal natural proppant consists of greater than 99 percent sand-sized quartz grains and also meets several other stringent standards set forth by the American Petroleum Institute.

Selected sandstone and sand samples were collected by personnel from the Geological Survey Program, Department of Environment and Natural Resources, from 10 different geologic units west of the Missouri River. Additional sand samples were obtained from fine-aggregate mine operators in western South Dakota.

Ultimately, 256 samples were collected for study; 243 underwent bulk sieve analysis to determine grain-size distribution, and photomicrographs were acquired of material retained on each sieve. Review of photomicrographs revealed that many sieves contained aggregates, which skewed weight distribution results. Due to budget constraints, further testing was not possible.

All of the samples failed to meet American Petroleum Institute recommended weight distribution specifications for natural proppants. Many samples collected from Tertiary- to Quaternary-age geologic units (White River Group, Arikaree Group, Ogallala Group, glacial outwash, terrace deposits, Sand Hills Formation, and alluvial deposits) have well-rounded and spherical grains, but most contain a significant amount of minerals other than quartz. Most samples collected from Jurassic- and Cretaceous-age geologic units (Hulett Sandstone Member of the Sundance Formation, Unkpapa Sandstone, Lakota Formation, Fall River Sandstone, and Fox Hills Sandstone), contain a significant amount of minerals other than quartz and/or contain angular and elongated grains. Samples collected from the Cambrian-Ordovician-age Deadwood Formation and Pennsylvanian-Permian-age Minnelusa Formation were determined (1) to be too fine-grained, (2) to be too hard due to carbonate or silica cement, (3) to contain angular and elongated grains, (4) to have significant iron staining, or (5) to contain a significant amount of minerals other than quartz.

None of the sand in South Dakota could likely be mined solely as hydraulic fracturing sand. In order to fully utilize a sand deposit and extract a marketable volume of sand from these sources, significant volumes of coarser or finer material would have to have a market as well. If there is demand for other uses, then the sand may be economical to mine.

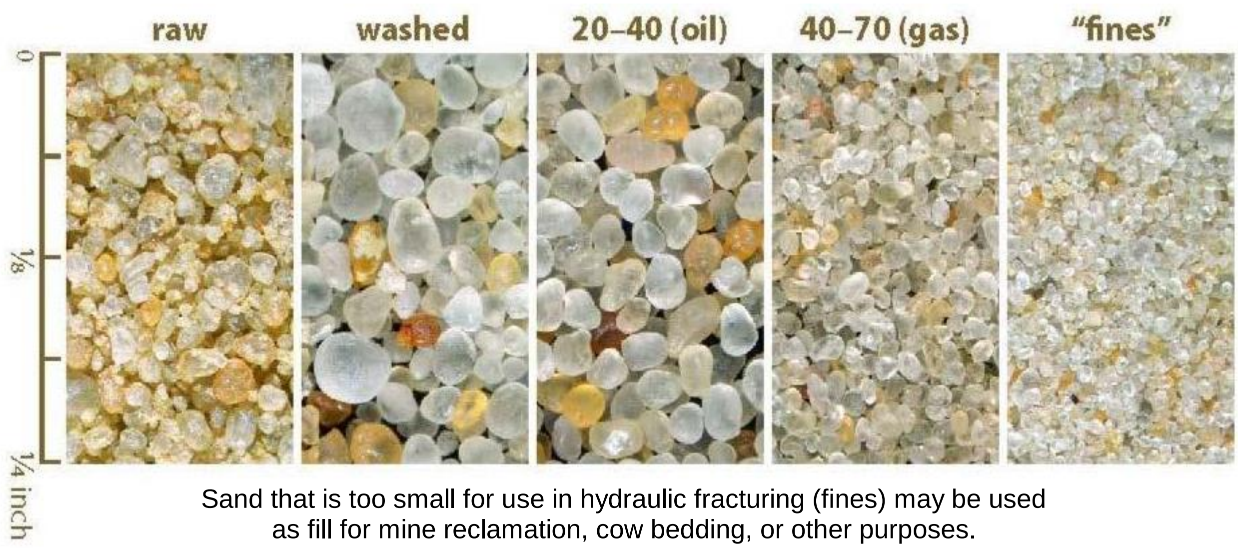
A literature review revealed no bauxite deposits have been mapped or described, nor is there definitive data to indicate the presence of significant kaolinite-rich sediments in South Dakota. Thus, it is not likely that South Dakota has the necessary raw materials needed for the manufacturing of ceramic proppants.

INTRODUCTION

Background

Most of the oil wells being drilled in the Williston Basin use hydraulic fracturing during the well completion process. The hydraulic fracturing technique forces a combination of water, proppants (natural sands, resin-coated sand, or synthetic ceramic spheres), and minor amounts of other chemicals into a well bore under high pressure. The intent of this technique is to create fractures in the tight reservoir rock. The proppants are used to keep the fractures open which leads to an increase in the flow of reservoir fluid into the well bore. The Bakken/Three Forks system in North Dakota consists of tight reservoir rocks, and increased drilling in this oil play has led to an increase in the demand for proppants. On average, each Bakken/Three Forks well needs 3 to 5 million pounds of proppant for completion. Over the next 20 years, the North Dakota Industrial Commission estimates that there will be 40,000 new wells drilled in western North Dakota.

Wisconsin has some of the best sand in the country that can be used for hydraulic fracturing because it is almost entirely quartz, and the grains are very spherical and rounded, extremely hard, and of a specific size range (fig. 1). In addition, the geologic formations being mined are near the surface and close to transportation corridors such as rail or barge (Wisconsin Geological and Natural History Survey, 2014), making them more economical to mine.



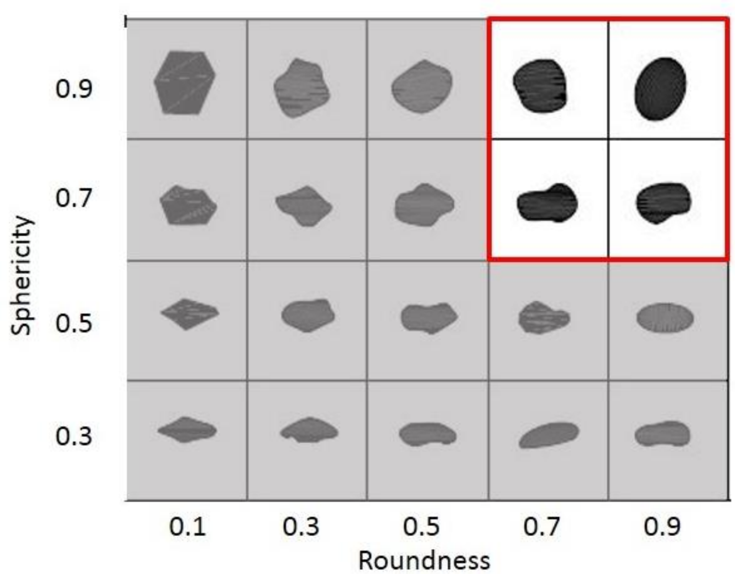
Modified from Wisconsin Geological and Natural History Survey (2014)

Figure 1. Hydraulic fracturing sand as it appears in the quarry (raw), washed to remove clay minerals, and sorted by size for various uses.

The American Petroleum Institute (API), the American National Standards Institute and the International Standards Organization (ISO) recommend testing methodologies and specifications for hydraulic fracturing sand (American Petroleum Institute, 1995; American National Standards Institute/American Petroleum Institute, 2008). The primary considerations are the physical aspects of the sand; size, sphericity, roundness, crush resistance, acid solubility, turbidity, density, and mineralogy. The specifications from the American Petroleum Institute and the American National Standards Institute are summarized in the remainder of this section of the report.

Grain sizes within an individual sand sample are determined by sieve analysis which reveals the grain-size distribution of a sample. The primary sand sizes used as proppants are in the 20/40 and 40/70 sieve sizes. For testing of the 20/40 size designation, sieves 16, 20, 30, 35, 40 and 50 are the recommended sizes. For testing of the 40/70 size designation, sieves 30, 40, 50, 60, 70 and 100 are recommended. The API recommends that at least 90 percent of a tested sand sample falls between the designated sieve sizes. In addition, not more than 0.1 percent should be larger than the first sieve size and not more than 1.0 percent should be smaller than the last sieve size. For example when testing the 20/40 size designation, no more than 0.1 percent of the sample should be retained on the 16 sieve and no more than 1.0 percent should be retained on the 50 sieve.

Sphericity and roundness are parameters used to evaluate the shape of a sand grain. Sphericity is a measure of how closely a sand particle approaches the shape of a sphere and roundness is a measure of the relative sharpness of grain corners (fig. 2). A value of 1.0 for sphericity and 1.0 for roundness indicate a theoretically perfect spherical and round grain. The API recommends that the sphericity and roundness of sand grains used as proppant should be 0.6 or greater. In addition to being spherical and well rounded, sands to be used as proppant should consist of single grains, meaning that the amount of aggregates (or clusters) should be minimal. A sand containing 1 percent or more aggregates is not considered suitable as a proppant.



Area highlighted in red indicates that sphericity and roundness factors are above 0.6, which is the American Petroleum Institute (API) recommended range for sand grains to be used in hydraulic fracturing. Area in gray indicates shape factors that do not meet API specifications. Modified from Krumbein and Sloss (1963).

Figure 2. Chart showing sphericity and roundness.

Crush-resistance is the resistance of a quartz grain under compressive loading. Crush-resistance tests are conducted on samples to determine the amount of proppant crushed at a given stress. Tests are conducted on samples that have been sieved so that all particles tested are within the specified size range. This test determines the strength of a sand grain and is important because it gives insight into how well sand grains will hold up under pressure. A sample is subjected to a predetermined level of stress and the resulting crushed material generated is measured in weight percent. Samples should not produce more than the maximum fines as shown in table 1. Crush resistance K-Value is the highest stress level at which no more than 10 percent crushed material is generated.

Mesh size	Load on cell (pound force)	Stress on sand in pounds per square inch	Suggested maximum percent of fines by weight
6/12	6,283	2,000	20
28/16	6,283	2,000	18
12/20	9,425	3,000	16
16/30	9,425	3,000	14
20/40	12,566	4,000	14
30/50	12,566	4,000	10
40/70	15,708	5,000	8
70/140	15,708	5,000	6

Modified from American Petroleum Institute (1995)

Table 1. Suggested maximum fines for frac sand crush resistance tests

Proppant sands may contain undesirable contaminants such as carbonates, feldspars, iron oxides, and/or clays. An acid solubility test will indicate the amount of undesirable contaminants and help in determining the suitability of a proppant in applications where the proppant may come into contact with acids. Acid-soluble material in a sand sample should not exceed 2.0 percent by weight for sand sizes in the 6/12 through 30/50 mesh sizes, and 3.0 percent for sand in the 40/70 through 70/140 mesh sizes.

Turbidity in water is due to suspended clay, silt, or finely divided inorganic matter. The turbidity of a sand sample is measured by determining the amount of light passing through a suspension of the sample that has been placed in distilled water. Sand to be used as proppant should have values of 250 Formazin Turbidity Units (FTU) or less.

Density values are important properties of proppants. The bulk density is used to determine the mass of a proppant needed to fill a fracture or storage tank. Apparent density is measured with a low-viscosity fluid that wets the particle surface, and it includes the pore space within an individual sand grain that is inaccessible to the fluid. Absolute density excludes pore space within an individual sand grain as well as void spaces between sand grains.

A qualitative x-ray diffraction test should be conducted on a representative sample of the sand to determine the mineralogical makeup of the sample. In terms of mineralogy, hydraulic-fracturing sand must consist of more than 99 percent quartz. Any mineral type present in excess of approximately 1 percent should be reported.

To increase their compressive strength, natural sand grains are coated with resin. Resin coating shields a grain from fracture closure stresses, prevents shattering, and contains any fines generated (Pallanich, 2013; Santrol, 2014). Resin-coated sand grains distribute closure stresses over a larger area, which allows grains to resist being compressed. The redistribution of stress also helps maintain porosity and reduce embedment of grains into fracture walls, which can constrict the fracture (Santrol, 2014). At certain downhole temperatures and pressures, resin-coated grains can be engineered to bond, forming a proppant pack, preventing sand grains from flowing back into the wellbore from the fracture (Pallanich, 2013). Coating a sand grain with resin does not improve its sphericity or roundness.

Due to budget constraints for this project, no samples were outsourced to laboratories capable of performing crush resistance, solubility, turbidity and density tests, nor were x-ray diffraction analyses able to be performed in house on any of the samples.

Engineered proppants made of aluminosilicate ceramic are an alternative to using sand. Ceramic proppants offer the advantages of uniform size and shape as well as higher crush strength. Bauxite and kaolin are the primary raw materials currently used in the manufacturing of aluminosilicate ceramic proppants. When fracture closure pressures are very high, ceramic proppants tend to perform better than natural sands but are costlier than natural sand proppants.

Purpose of Study

The impetus behind this study is the current, high demand for proppant in the United States. Because of the oil boom occurring in North Dakota, the Geological Survey Program, South Dakota Department of Environment and Natural Resources, has been contacted by numerous individuals requesting information regarding sand resources in South Dakota. Prior to this study, no other state-wide investigation had been completed specifically addressing sand resources as potential natural proppants, or alumina resources that could be used to manufacture synthetic proppants. The Geological Survey Program undertook this study from October of 2012 to February of 2014. The purpose of this study was to: 1) characterize selected sand bearing formations in South Dakota for potential use as natural proppants and 2) determine if there are any bauxite or kaolin resources suitable for manufacturing of ceramic proppants.

Previous Investigations

Sand Resources for Silica Use

Ching (1973) investigated the Deadwood Formation to determine if it could be used as a high-silica resource. He specifically looked at its suitability for use as; abrasives, building products, glass, hydraulic fracturing, or refractory purposes, as well as other miscellaneous uses.

He measured section, described the lithology, and acquired 139 samples at 23 different locations around the Black Hills. In addition, he sampled the Lakota Formation at four locations and a Quaternary wind-blown sand at one location. All of the samples were crushed, ball-milled, and subjected to a sieve analysis. Six of the Deadwood Formation samples were analyzed for weight percent of SiO_2, Fe_2O_3, Al_2O_3, TiO_2, CaO, and MgO, and for ignition loss at 900ºC. Ching concluded that at three of the locations, the Deadwood Formation had potential for use as hydraulic fracturing sand.

Huq (1983) studied the Deadwood Formation along the northeastern flank of the Black Hills, investigating the potential of the basal sand for use in hydraulic fracturing. He narrowed his study area to the Nemo, Piedmont, and Pactola Dam geological quadrangles and studied nine individual sites within those quadrangles. Huq (1983) compiled detailed outcrop descriptions at each site and collected 332 samples for laboratory studies. Of the 332 samples, he selected those from each site which had potential for use as hydraulic fracturing sand and subjected them to sieve analysis. Atomic adsorption was used to acquire chemical analyses of composite samples from each of the nine sites. Huq (1983) found that the sands best suited for hydraulic fracturing are in close proximity - either overlying or adjacent to - Precambrian quartzite and concluded that the potential for sand deposits suitable for hydraulic fracturing in the eastern Black Hills are positive.

Haggar and others (2002) completed sieve analyses on 44 samples from quartz-rich sand and gravel bodies in southeastern South Dakota. From these analyses, histograms, cumulative curves, and statistical measures were compiled. The report was the first part of a multi-phase investigation to classify the geologic age and provenance of western-derived sediments.

Chadima (2012) investigated an abandoned sand and gravel mining operation in Marshall County, South Dakota, to determine if it could be a potential source of sand for hydraulic fracturing operations. The majority of the remnant mine materials were mounded into large piles of mixed particles sizes (silt, sand, gravel, cobbles). Nine samples were collected, deliberately avoiding the cobbles. Particle size sieve distribution analysis and mineralogical estimations showed that glacial outwash is not a viable source for use as hydraulic fracturing proppant.

Raw Materials for Ceramic Proppant

The primary raw materials used to manufacture ceramic proppants are bauxite and kaolin. No bauxite deposits are known to exist in South Dakota, therefore this portion of the study focused on potential kaolin deposits. High-aluminum kaolin contains 25 to 35 percent alumina by weight and serves as a raw material for ceramic proppants.

North Dakota has two kaolinite-rich geological units; both of these, the Paleocene-age Rhame Bed of the Slope Formation, and the Paleocene- to Eocene-age Bear Den Member of the Golden Valley Formation are found in southwestern North Dakota. Murphy (2012b, 2013) collected more than 200 samples from these two formations and analyzed them for their alumina content. The alumina content was found to range in mass percentage from 6 to 27 with a mean of

18 percent in the Rhame Bed, and from 7 to 34 percent with a mean of 21 percent in the Bear Den Member (Murphy, 2012a).

Occurrence of the Rhame Bed and the Bear Den Member in southwestern North Dakota prompted a review of scientific literature in order to determine if these units may correlate with any units in northwestern South Dakota. The Slope Formation and the Bear Den Member of the Golden Valley Formation are not formally recognized rock units in South Dakota.

In North Dakota, the Rhame Bed typically consists of a sequence of two dominant lithologies: a discontinuous cap composed primarily of silcrete which may be a few inches to a few feet thick that is underlain by a deep-weathering profile enriched in kaolinite (Wehrfritz, 1978; Murphy, 2013). The average thickness of the Rhame Bed silcrete is 1.4 feet (0.43 m), and the underlying kaolinitic sediment has an average thickness of approximately 20 feet (6 m) (Wehrfritz, 1978).

Numerous geologists have recognized and described Paleocene-age silcretes in South Dakota (Todd, 1898; Winchester and others, 1916; Denson and others, 1959; Pipiringos and others, 1965; Bolin 1956a and 1956b; Curtiss 1955a and 1955b). Upper-Paleocene age Tongue River Formation silcretes have been described in northwestern South Dakota at North Cave Hills, and on Anarchist Butte (Pipiringos and others, 1965). In addition, Paleocene-age silcretes have been identified in the Slim Buttes area, as well as at a few other locations (Todd, 1898; Winchester and others, 1916; Denson and others, 1959). The Tongue River Formation silcretes in South Dakota may be correlative with the Rhame Bed silcretes of North Dakota. The average thickness of these silcretes in South Dakota is unknown. In general, the presence of kaolinite in sediments beneath South Dakota silcretes has not been addressed in the literature; kaolinite has only been mentioned beneath silcrete outcrops in the North Cave Hills and at Anarchist Butte.

In North Dakota, the Golden Valley Formation consists of two members, the upper Camels Butte Member and the lower Bear Den Member. The Camels Butte Member is characterized by the presence of fossil megaspores of the distinctive floating fern *Salvinia* in its basal portion, and by micaceous sediments throughout (Hickey, 1977). It is yellow to tan in color consisting of strata containing illite and montmorillonite clay minerals. The underlying Bear Den Member is recognized by its kaolinite clay content and strata that weather into three distinctly colored zones: a basal gray, middle orange, and an upper carbonaceous purplish gray (Hickey, 1977). Kaolinite is overwhelmingly prevalent in the orange zone where it averages more than 80 percent of the total clay fraction (Hickey, 1977; Clechenko, 2004). The upper boundary of the Bear Den Member is a thin bed of lignite or its lateral equivalent: a silicified siltstone (silcrete), or freshwater limestone (Hickey, 1977). The thickness of the Bear Den Member ranges from 5 to 65 feet (2 to 20 meters), with the kaolinite-enriched zone averaging 25 feet (7.6 meters) in thickness (Hickey, 1977).

In South Dakota, an Eocene-age stratigraphic unit named the Slim Buttes Formation was introduced as a rock sequence in Harding County (Malhotra and Tegland, 1960). Malhotra and Tegland (1960) evaluated the mineralogy of the Slim Buttes Formation and found the heavy mineral content to ubiquitously contain biotite mica. Fossil megaspores of the fern *Salvinia* have been found in the Slim Buttes area (Jain and Hall, 1969). Agnew and Tychsen (1965) suggested that the Slim Buttes Formation "may be the same as the Golden Valley Formation of southwestern North Dakota, but further work is needed to substantiate it." This same correlation was also suggested by Skinner (1951).

At this time no commercial venture to mine North Dakota kaolinite has been pursued. In South Dakota, no definitive data exist to suggest the presence of significant kaolinite-rich sediments.

METHODS

Selection of Geologic Units to be Sampled

In order to determine potential units to be sampled, descriptions of geologic formations were reviewed using Agnew and Tychsen (1965) and Martin and others (2004). The surface geology east of the Missouri River was excluded from consideration because it consists mostly of glacial deposits, which are geologically young and have not undergone the geological processes necessary to produce sufficiently mature sediments. Furthermore, Chadima (2012) determined that glacial outwash east of the Missouri River is not suitable as hydraulic-fracturing proppant. Factors considered in inclusion or elimination of geologic units west of the Missouri River were thickness of sandstone/sand beds, amount of quartz in sandstone/sand, and extent of surface exposures. After review, 10 geologic units were chosen for sampling of surface exposures: the Deadwood Formation, Minnelusa Formation, Hulett Member of the Sundance Formation, Unkpapa Sandstone, Lakota Formation, Fall River Sandstone, Fox Hills Sandstone, Arikaree Group, Ogallala Group, and Sand Hills Formation.

Description of Geologic Units

Deadwood Formation

The Deadwood Formation, Lower Ordovician and Middle Cambrian in age, consists of glauconitic conglomerate, sandstone, shale, dolomitic-limestone, and dolomite. The unit ranges from 4 to 400 feet (1 to 122 meters) in thickness (Martin and others, 2004), thinning from north to south. The Deadwood Formation crops out exclusively in the Black Hills, nearly encircling the crystalline Precambrian core; the lower contact with Precambrian rock units is unconformable as evidenced by its lowermost conglomerates.

Minnelusa Formation

The Minnelusa Formation, Lower Permian to Middle Pennsylvanian in age, consists of interbedded sandstone, siltstone, shale, limestone, dolomite, chert, and breccia (Martin and others, 2004). The Minnelusa Formation crops out exclusively in the Black Hills. In the northern Black Hills, the thickness averages about 500 feet (152 meters), and in the southern Black Hills, the thickness ranges from 450 to 700 feet (137 to 213 meters) (Jennings, 1959). From field observations in the northern Black Hills, thick sandstone beds are dominant; however, many are indurated. Along the southwestern flank of the Black Hills, the Minnelusa Formation crops out more extensively and is more dolomitic. In Redbird Canyon, in extreme southwestern Pennington County and northwestern Custer County near the Wyoming border, there are exposures of very friable, cross-bedded Minnelusa Formation sandstones.

Hulett Sandstone Member of the Sundance Formation

The Hulett Sandstone Member of the Sundance Formation, Middle Jurassic in age, is not well exposed along the margins of the Black Hills uplift, and outcrops and road cuts are few. However, Imlay (1947) noted that the Hulett Sandstone Member is better exposed along the south and southeastern portions of the Black Hills with a thickness of 25 to 55 feet (7.6 to 17 meters) where it is characterized by thin-bedded sandstone interbedded with shale. It irregularly thickens to 120 feet (36.5 meters) northward along the eastern and northeastern flanks of the Black Hills to a harder, more massive sandstone. Based on field observations, the Hulett Sandstone Member consists of thin- to medium-bedded, cross-bedded, silty, fine-grained sandstone with shaly partings, bioturbation, and numerous sedimentary structures including truncated ripple marks and runzelmarken (Rautman, 1978).

Unkpapa Sandstone

The Unkpapa Sandstone, Upper Jurassic in age, is exposed along the margins of the Black Hills uplift. Martin and others (1996) noted that the Unkpapa Sandstone occurs only in the southern half of the Black Hills. Gries (1952) restricted the Unkpapa Sandstone to the eastern and southern edges of the Black Hills while acknowledging remnants in the northern part. Redden and DeWitt (2008) noted that the Unkpapa Sandstone extended to the northwest of Sturgis in the northern Black Hills, ultimately intertonguing with the Morrison Formation.

The Unkpapa Sandstone consists of flaggy- to massively-bedded, fine- to very-fine-grained, argillaceous, quartzose sandstone. Gott and others (1974) classified the sandstones of the Unkpapa as feldspathic orthoquartzites. In the localities where it was sampled for this project, the Unkpapa Sandstone was slightly-lithified to friable. With a thickness up to 267 feet (81.4 meters), the Unkpapa Sandstone is thickest along the southeastern flank of the Black Hills, especially near Buffalo Gap in Custer County (Waage, 1959). In the northern Black Hills, Imlay (1947) noted a thickness of 30 to 150 feet (9.1 to 45.7 meters).

Lakota Formation

The Lakota Formation, Early Cretaceous in age, consists of claystone, silty pebble conglomerate, and massive- to thin-bedded, cross-bedded sandstone (Martin and others, 2004). The sandstones consist mostly of quartz and some of the sandstones consist of more than 90 percent quartz (Gott and others, 1974). Minor constituents in all of the sandstones are feldspar, chert, clay, magnetite, and zircon; for the most part, they are fine- to medium-grained, well-sorted, locally calcareous, and rounded to subrounded (Gott and others, 1974). The Lakota Formation ranges from 35 to 100 feet (11 to 30.4 meters) in thickness (Martin and others, 2004).

In the southwestern Black Hills, at many localities in Fall River and Custer Counties, very friable sandstone beds of the Lakota Formation were encountered. Other friable Lakota sandstones were identified in outcrop or sent in by fine-aggregate mine operators from southwestern Meade County.

Fall River Sandstone

The Fall River Sandstone, Early Cretaceous in age, consists of calcareous mudstone and shale, siltstone, cross-bedded, fine-grained, micaceous, ferruginous, locally calcareous sandstone, and thin streaks and seams of coal and carbonaceous shale (Martin and others, 2004). Waage (1959) described the Fall River Sandstone as predominantly sandstone with some interbedded shale and siltstone; he also gave a thickness of 110 to 160 feet (33.5 to 48.8 meters) in the Black Hills. He listed several defining characteristics for the formation such as fine grain size, laminated mudstones and siltstones, tabular, laminated to cross-bedded sandstones, and abundant sedimentary structures (Waage, 1959). From the southern Black Hills, the Fall River Sandstone thins northward (Waage, 1959). In the southern Black Hills, sandstone beds are frequently massive, but north of Hermosa, South Dakota, the massive sandstone beds become thinner and less frequent and are replaced with interbedded sandstone, siltstone, and shale (Waage, 1959).

Fox Hills Sandstone

The Fox Hills Sandstone, Late Cretaceous in age, consists of fine- to coarse-grained cross-bedded sandstone, argillaceous sandstone, arenaceous shales, ferruginous stringers, and siltstones, and ranges from 25 to 400 feet (7.6 to 122 meters) in thickness (Martin and others, 2004). The Fox Hills Sandstone extends from Harding and Butte Counties in the west to Jackson, Haakon, Ziebach, Dewey, and Corson Counties in the east (Martin and others, 2004). The Fox Hills Sandstone in Harding and Butte Counties was an ancient delta that built eastward into the Fox Hills Sea, which covered what is currently Jackson, Haakon, Ziebach, Dewey, and Corson Counties (Hoganson, 2007).

In a delta environment, coarser sand is deposited in river channels on the delta and in sand bars along the shorelines. The finer sand along with silt and clay is carried out by the rivers and deposited along the sea bed further away from the delta. Therefore, the coarsest sand in the Fox Hills Sandstone should be found in Harding, Butte, and northwestern Meade Counties, at the delta margins.

Arikaree Group

The Arikaree Group is Oligocene and Miocene in age and consists of siltstone, sandstone, volcanic ash, claystone, and marl (Martin and others, 2004). The Arikaree Group crops out extensively in southwestern and south-central South Dakota, and isolated outcrops are found at West and East Short Pine Hills and Slim Buttes in Harding County (Baker, 1952; Martin and others, 2004).

In northwestern Nebraska, Schultz (1938) described 200 feet of fine-grained, friable sandstone in the Arikaree Group; in south-central Shannon County, the Arikaree Group consists of gray, massive, noncalcareous, moderately consolidated, fine- to very-fine-grained sandstone with interbedded marl and limestone, some of which may be nodular (Harksen, 1965). However, past analysis of some sandstones from the Arikaree Group indicates mostly fine to very-fine grain size consisting of a significant fraction of volcanic materials (Harksen and Macdonald, 1969).

Ogallala Group

The Ogallala Group, Pliocene and Miocene in age, consists of sandstone, calcareous sandstone, silty limestone, fluvial siltstones, claystone with interbedded sandstone, bentonitic clay, conglomerate, and western-derived gravels (Martin and others, 2004). The Ogallala Group is found in south-central South Dakota and extends directly eastward from Shannon County to Gregory County (Martin and others, 2004). Isolated outliers of Ogallala Group are found in Jackson, Mellette, northern Tripp, Lyman, Brule, and extreme northwestern Charles Mix Counties (Martin and others, 2004).

Well-cemented sandstones, volcanic ash, and lacustrine limestones and indurated sandstones and siltstones, informally known as “mortar beds” are common in the upper part of the Ogallala Group (Sevon, 1960; Harksen and Macdonald, 1969). The lower Ogallala Group generally consists of friable, fine- to medium-grained, well sorted, locally calcareous, subangular to subrounded, arkosic sandstone (Collins, 1959). Local cross-bedding is evident in addition to a quartz- and feldspar-pebble conglomerate with localized calcite cement in the lower part (Collins, 1959). Volcanic ash beds might be locally present throughout the unit (Collins, 1960; Sevon, 1960).

Sand Hills Formation

The Sand Hills Formation, Quaternary in age, consists of eolian sand deposits derived from Tertiary sandstones; it is primarily exposed in southern Bennett, Todd, and southeastern Shannon Counties. The Sand Hills Formation consist of fine- to medium-grained sand reworked by wind into dunes, some up to 160 feet high (Collins, 1959). The sand is unconsolidated, rounded to well-rounded and consists mostly of quartz with some feldspar (Sevon, 1960). Because the sand is mostly derived from the Arikaree and Ogallala Groups, it is locally calcareous, and there is difficulty distinguishing the Sand Hills Formation from older deposits in some areas (Filipovic, 2011). There has been some migration of the dunes and blowouts between them, but most of the dunes are being vegetated which stabilizes them. The maximum thickness of the Sand Hills Formation in South Dakota is approximately 200 feet (61 meters).

Acquisition of Samples

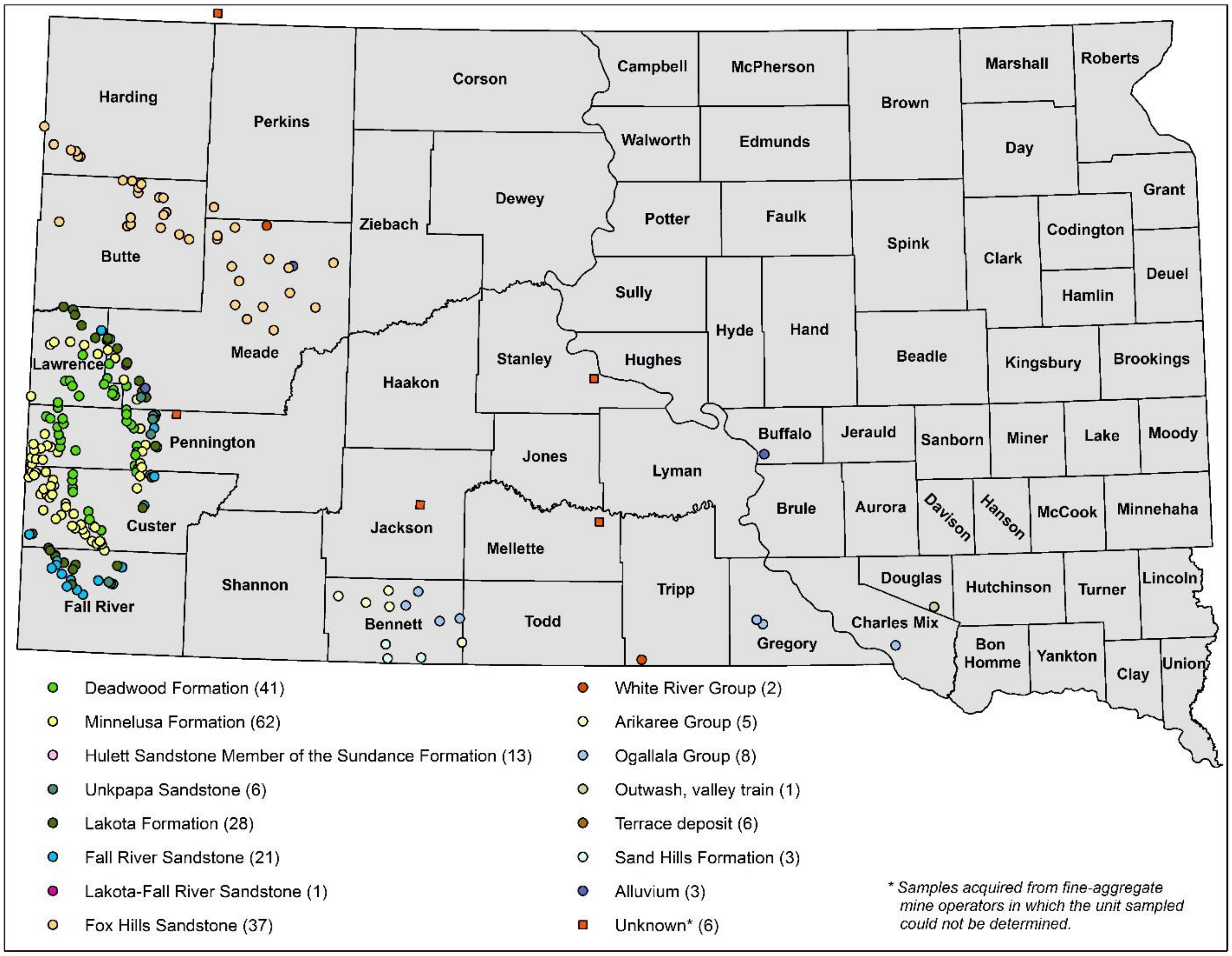
Sampling by Geological Survey Program staff commenced during the last week of November 2012 and concluded in late July 2013. The project focused on three main areas: the Black Hills, Bennett County, and the Fox Hills Sandstone exposures in Harding, Butte, and Meade Counties.

Samples were collected from surface exposures. Once a surface exposure was chosen for sampling, it was cleared of debris to reduce potential contamination. Where surface exposures were friable, composite channel samples were collected. Otherwise, “grab” samples were obtained which consisted of breaking off a fist-sized chunk of the geologic unit every few feet within the sample interval or collecting float along the surface exposure. Approximately 12 pounds of representative sample were collected and placed into a cloth bag. During collection, pictures were taken of the sampling location, and the latitude and longitude were acquired using a Garmin GPSMAP® 60CSx handheld Global Positioning System.

In February 2013, samples of sandstone/sand were solicited via letter from fine-aggregate mine operators having mailing addresses in western South Dakota. Although this solicitation for samples was not restricted to specific geologic units, a copy of some general specifications from the American Petroleum Institute regarding the suitability of sand for use in hydraulic fracturing applications was provided to the operators. If the operators thought that their aggregate might meet the specifications, the operators were invited to send a 5 pound sample to the Geological Survey Program for analysis. The sample location and the Geologic Map of South Dakota (Martin and others, 2004) were used to determine the geologic unit sampled, if possible.

A total of 231 samples were collected from surface exposures in the field and another 26 samples were received from fine-aggregate mine operators. Fourteen of these samples were not processed due to reasons described in the “Processing of Samples” section of this report. The sample locations of the remaining 243 samples processed are shown in figure 3.

Several samples received from fine-aggregate mine operators were determined to be acquired from the Lakota Formation and Unkpapa Sandstone; those geologic units are described above. It was determined that the rest of the samples received from mine operators were acquired from the Tertiary White River Group or Quaternary unconsolidated deposits (outwash valley train, terrace deposits, and alluvium). There were six samples in which the geologic unit could not be identified with the information provided. In this situation, the geologic unit of origin was classified as Unknown, however, most of these samples are probably Quaternary in age.



Numbers in parentheses indicate the number of samples collected for that geologic unit.

Figure 3. Locations of sand bearing geologic units sampled and locations of samples submitted by fine-aggregate mine operators.

Sample Locations

Locational information for the 243 samples that were processed are available in a Microsoft® Excel file at http://sddenr.net/fracsand/hfsc-locational-data.xlsx. The Excel file includes information on sample location, formations sampled, intervals sampled, and links to field photographs, field data sheets, and the sieve results.

Processing of Samples

All samples were assessed in the laboratory in order to determine if they were consolidated/cemented or unconsolidated. Consolidated/cemented samples were passed through a Braun Chipmunk VD67 crusher for disaggregation. Pieces of rock too big to fit into the crusher were initially broken with a hammer before being placed in the crusher. The entire sample was passed through the crusher to help homogenize it. Unconsolidated samples were not run through the crusher since no further disaggregation was needed.

Samples were tested for the presence of carbonate minerals by applying dilute hydrochloric acid. Next, samples were divided into two equal portions by pouring them into a sample splitter. The sample was divided until approximately 80 to 120 grams of sample were collected.

Prior to disaggregation, samples HFSC-2012-009, HFSC-2012-034, HFSC-2012-050, HFSC-2012-070, HFSC-2012-073, HFSC-2013-081, HFSC-2013-082, HFSC-2013-088, HFSC-2013-095, HFSC-2013-118, HFSC-2013-122, and HFSC-2013-235 were removed from the study because upon visual inspection it was determined that they contained greater than 75 percent clay. Sample HFSC-2013-256 was removed from the study because it was determined to be weathered phonolite and contained no sand grains. Sample HFSC-2013-106 was removed from the study because it was suspected of having been contaminated with sample HFSC-2013-107.

Further disaggregation was accomplished by pouring the sample split through a 4 sieve to collect any oversized rocks and/or larger aggregates. The oversized rocks were removed, weighed and noted on the sieve data sheet. Larger aggregates were placed in an iron mortar and pounded gently with a pestle in an up and down motion, as prescribed by Folk (1980). The remaining sample that passed through the 4 sieve was spread out onto a flat metal pan and rolled over with a rolling pin. The rolling pin was used until it appeared there were no more aggregates present. Due to the hardness of many of the samples it was impossible to fully disaggregate all the samples. Disaggregated material from the iron mortar and metal pan were recombined to be sieved.

Every 20th sample was processed as a duplicate, to check for consistency in the disaggregation method. A hardness descriptor (unconsolidated, very friable, friable, fairly friable, soft, fairly soft, fairly hard, hard, and very hard) was noted on each sieve data sheet, to provide a general overview on the difficulty of disaggregating the sample.

Samples ready to be sieved were weighed on a Mettler Toledo AE160 balance. Samples weighing more than 120 grams were placed on a piece of wax paper, and a quartering technique was employed until the weight was reduced to between 80 and 120 grams.

ANALYSIS OF SAMPLES

Sieving of Samples

Sieving was accomplished using Fisherbrand U.S. Standard 8-inch diameter brass sieves. A W.S. Tyler Ro-Tap was used to mechanically shake the sieves. The Ro-Tap can only hold six nested sieves plus the pan, so two sieve stacks were used. The first sieve stack consisted of the 16, 20, 30, 35, 40, and 50 sieves; the second stack consisted of the 60, 70, 100, 120, 140, and 5 (as a place holder) sieves. Each sample was poured into the first stack of sieves and was shaken in the Ro-Tap for 10 minutes. Once shaking was complete on the first stack, the pan contents were poured into the second stack of sieves and was shaken in the Ro-Tap for an additional 10 minutes.

To remove as many grains as possible from the sieve screens, each sieve was inverted over a piece of creased aluminum foil and gently tapped to loosen grains. The screen was then gently worked with a brass and/or nylon brush in a circular motion. The grains that collected on the foil were poured into a weighing boat and then weighed.

After weighing, each sieve fraction was photographed using a Leica EZ4HD stereo microscope with an integrated 3.0 mega-pixel CMOS camera connected to a Gateway E-155C laptop. A small amount of material from each sieve fraction was spread out over a black background. The sieve fraction was positioned under the microscope until numerous grains with some separation between them could be seen. Photomicrographs were captured and annotated using Leica LAS EZ software. Material retained on the 16 to 40 sieves were photographed at 8X magnification. Material retained on the 50 sieve to the pan was photographed at 30X magnification.

Percent Aggregate Estimation

Photomicrographs were used to estimate the amount of aggregates retained on each sieve. Due to the difficulty in estimating exact percentages, four divisions were used to classify the amount of aggregates retained on each sieve: 100 percent (all aggregates), greater than 70 percent (99% to 70% aggregates), 30-70 percent and less than 30 percent (0 to 30% aggregates). A designation of NA (not applicable) means nothing was retained on that sieve fraction.

Effect of Aggregates on Sieve Data

The quantity of aggregates composed of smaller grains cemented together presented a problem in conducting a meaningful analysis of the sieve data. Recommendations by API regarding sampling and testing are for samples that are being supplied by the sand supplier or service company to the user, meaning that the sand has potentially undergone several processing steps. Data from this study should be considered as being acquired from “raw” materials that have undergone only one processing step (crushing). Samples containing more than 1 percent aggregates could not be strictly evaluated using API-recommended size-distribution specifications. However, sieve results are generally presented as if the samples qualified for evaluation under the API standards because there are no available standards for raw material.

Qualitative Assessment of Mineralogy, Sphericity, and Roundness

A qualitative analysis of all samples was completed. This analysis incorporated all available information for each sample. Sieve weight data were used in conjunction with the photomicrographs to determine if the sample contained a significant amount (visual estimate of >10%) of clay, minerals other than quartz, and/or rock fragments. Photomicrographs were used to estimate the sphericity and roundness (i.e., angular or rounded, spherical or elongated) of individual grains.

RESULTS

Sieve Analysis

Sieve analysis was conducted on 243 samples. Twenty five of these samples were received from fine-aggregate mine operators. Information on location and a summarization of sieve weight data for each sample is presented in table format in the appendix.

Sieve results data are available in a Microsoft® Excel file at http://sddenr.net/fracsand/hfsc-sieve-data.xlsx. Clicking on an individual sample number link will open a separate worksheet that contains two charts (a histogram and a grain-size distribution curve), a percent aggregate estimation, a hardness description, and whether or not the sample reacted to hydrochloric acid. Within this worksheet are links to the sieve photomicrographs and to the worksheet containing sieve data. Care should be taken when interpreting charts without consulting other data provided (photomicrographs and aggregate estimation) because the charts do not reveal the amount of aggregates present on each sieve.

Results from Geologic Units Sampled

Deadwood Formation

Of the 41 samples collected from the Deadwood Formation, all failed to meet API-recommended size distribution specifications. All of the samples had more than 0.1 percent retained on the 16 sieve and more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

Most of the Deadwood Formation samples are hard and cemented with silica or calcite, and most contain a significant amount of minerals other than quartz, rock fragments, and/or aggregates. The majority of the quartz grains in all the Deadwood Formation samples are angular, elongated, and/or moderately- to severely-iron stained.

Minnelusa Formation

Of the 62 samples acquired from the Minnelusa Formation, 14 had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

Most of the Minnelusa Formation samples tested positive for carbonates (11 did not) and most contain a significant amount of clay or minerals other than quartz. Because many

Minnelusa Formation samples are fine grained and cemented with carbonates, weight percentages on the 40 and coarser sieves are primarily aggregates.

Hulett Sandstone Member of the Sundance Formation

All 13 samples collected from the Hulett Sandstone Member of the Sundance Formation tested positive for carbonate minerals. Almost without exception, all sieves but the 140 sieve and pan contained 100 percent aggregates, indicating very-fine-grained sandstone, well- to loosely-cemented with carbonates. One of the samples had less than 0.1 percent retained on the 16 sieve, however, all failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All of the samples from the Hulett Sandstone Member of the Sundance Formation appeared to consist of predominantly quartz with only minor amounts of minerals other than quartz. The majority of the grains for all samples are angular and would not meet API sphericity and roundness specifications.

Unkpapa Sandstone

Of the six samples collected from the Unkpapa Sandstone, three had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All of the samples collected from the Unkpapa Sandstone appear to consist predominantly of quartz with only minor amounts of minerals other than quartz.

Lakota Formation

Of the 28 samples collected from the Lakota Formation, 14 had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because all had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

The majority of the Lakota Formation samples contain a significant amount of minerals other than quartz or rock fragments, and most of the quartz grains are too angular to meet API sphericity and roundness specifications.

Fall River Sandstone

Of the 21 samples collected from the Fall River Sandstone, 5 had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

The majority of the Fall River Sandstone samples contain a significant amount of clay, minerals other than quartz, or rock fragments. For those few samples that appear to be dominantly quartz, the majority of the grains are angular and would not meet API sphericity and roundness specifications.

Lakota Formation or Fall River Sandstone

A single sample was collected from an undifferentiated sandstone in the Inyan Kara Group and could not be determined in the field to be definitively from either the Lakota Formation or the Fall River Sandstone. Thus, for the purposes of this study, the geologic unit was assigned as Lakota-Fall River Sandstone. This sample failed to meet API-recommended size distribution specifications because more than 0.1 percent was retained on the 16 sieve and more than 1.0 percent was retained on the 100 and finer sieves. This sample did not have more than 90 percent retained on the 20/40 or 40/70 sieves.

This sample consists predominantly of quartz with only minor amounts of minerals other than quartz.

Fox Hills Sandstone

Of the 37 samples collected from the Fox Hills Sandstone, 8 had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

In addition, all of the Fox Hills Sandstone samples contain a significant amount of clay, minerals other than quartz, and/or rock fragments.

White River Group

Two samples were collected from the White River Group. These samples failed to meet API-recommended size distribution specifications because they had more than 0.1 percent retained on the 16 sieve and more than 1.0 percent retained on the 100 and finer sieves. Neither sample had more than 90 percent retained on the 20/40 or 40/70 sieves.

One of the White River Group samples contains a moderate amount of minerals other than quartz. The majority of the grains are angular and would not meet API sphericity and roundness specifications. The other White River Group sample is composed almost entirely of clay.

Arikaree Group

Of the five samples collected from the Arikaree Group, two had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All Arikaree Group samples contain a significant amount of minerals other than quartz and/or rock fragments.

Ogallala Group

Of the eight samples collected from the Ogallala Group, two had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

Two samples are unconsolidated and the grains have relatively high sphericity and roundness, but all of the Ogallala Group samples contain a significant amount of clay, minerals other than quartz, and/or rock fragments.

Outwash, valley train

A single sample was collected from a glacial valley train outwash. This sample failed to meet API-recommended size distribution specifications because it had more than 0.1 percent retained on the 16 sieve and more than 1.0 percent retained on the 100 and finer sieves. This sample did not have more than 90 percent retained on the 20/40 or 40/70 sieves.

The glacial outwash sample is unconsolidated, has rounded and spherical to angular and elongated grains, and contains a significant amount of minerals other than quartz.

Terrace deposits

All six samples collected from terrace deposits failed to meet API-recommended size distribution specifications. All of the samples had more than 0.1 percent retained on the 16 sieve and more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All of the terrace-deposit samples are unconsolidated. However, all of the samples contain a moderate to significant amount of minerals other than quartz, and/or rock fragments. Grains range from being fairly rounded and spherical to angular and elongated.

Sand Hills Formation

All three samples collected from the Sand Hills Formation had less than 0.1 percent retained on the 16 sieve. However, all samples failed to meet API-recommended size distribution specifications because they had more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All Sand Hills Formation samples contain a significant amount of minerals other than quartz, although most grains are well rounded and spherical.

Alluvium

All three of the samples collected from alluvium failed to meet API-recommended size distribution specifications. All of the samples had more than 0.1 percent retained on the 16 sieve and more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All alluvial deposit samples contain a moderate to significant amount of minerals other than quartz, rock fragments and/or aggregates. Grains range from being fairly rounded and spherical, to angular and elongated.

Unknown

Six samples received by fine-aggregate operators were classified as originating from an unknown geologic unit because insufficient information was provided by the operator. All of these samples failed to meet API-recommended size distribution specifications. All of the samples had more than 0.1 percent retained on the 16 sieve and more than 1.0 percent retained on the 100 and finer sieves. None of the samples had more than 90 percent retained on the 20/40 or 40/70 sieves.

All of the samples classified as originating from an unknown geologic unit contain a moderate to significant amount of minerals other than quartz or rock fragments. Grains range from being fairly rounded and spherical, to angular and elongated.

CONCLUSIONS

Recommendations by API regarding sampling and testing are for samples that are being supplied by the sand supplier or service company to the user, meaning that the sand has potentially undergone several processing steps. Data from this study should be considered as being acquired from “raw” materials that have undergone only one processing step (crushing). As noted in a publication by the Wisconsin Department of Natural Resources (2012), larger mines may have crushing plants with a primary and secondary crusher. Once the rock is broken down by the crushers, the resulting material is conveyed to a screen plant where it is sorted by size. Particles that are of the desired size are moved to stockpiles and larger particles that have not been fully disaggregated are recycled within the crushers until they have been disaggregated to the desired size. Once disaggregated, the sand goes through a processing plant where it is washed, dried, and sorted (fig. 2). Washing removes unwanted minerals, silt, clays, or other inorganic fines. After washing, the sand may be dried and further sorted by screening.

A total of 243 sand samples were analyzed for their suitability as natural proppant for hydraulic fracturing. None of the samples collected for this study met API recommended specifications that at least 90 percent of tested sand sample fall between the 20/40 or 40/70 designated sieve sizes. In fact, none of the samples had 90 percent of the tested sample fall between the 20/70 sieve sizes. Several samples met the API recommendation that no more than 0.1 percent should be larger than the first sieve size but all the samples failed to meet the recommendation that no more than 1.0 percent of the sample be smaller than the last sieve size.

The crushing techniques used in this study could not fully disaggregate samples which were cemented, leaving many aggregates in the processed sample. Some beds within a geologic unit may be more friable while others are harder and more cemented. If both the friable and harder beds were included in a single field sample, laboratory sample processing was affected because larger, harder fragments were difficult to break down and “shielded” smaller aggregates from being broken down further during rolling pin processing. Additional crushing and washing of samples obtained from this study may liberate more grains from aggregates and rid the sample of unwanted minerals, silt, clays, or other inorganic fines. Further disaggregation of these samples would change the weight distribution on the sieves and therefore would affect the sieve weight data.

When the photomicrographs shown in figure 1 are compared to those acquired in this study, it is evident that none of the samples from this study approach the quality of sand that is currently being mined in Wisconsin. Most samples acquired for this study were too fine-grained, were too hard, contained a significant amount of minerals other than quartz, and would require significant washing and/or mechanical and chemical processing in order to approach API specifications.

A few of the samples from this study likely contain some percentage of grains that would meet some of the API-recommended specifications. The challenge noted by Anderson (2011) for North Dakota sand resources is extracting a marketable volume of proppant sand from a deposit containing a wide range of grain sizes. Significant volumes of coarser or finer material would also require markets in order to fully utilize the deposit. This “multiple markets approach” is detailed in Anderson (2011) and holds true for sand sources in South Dakota; none are suitable to be mined solely as hydraulic fracturing sand but if there is demand for other uses, then some of South Dakota's sand may be economical to mine.

A literature review revealed that no bauxite deposits have been mapped or described, nor is there definitive data to indicate the presence of significant kaolinite-rich sediments in South Dakota. Thus, it is not likely that South Dakota has the necessary raw materials needed for the manufacturing of ceramic proppants.

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APPENDIX

Sample locations and summary of sieve weight data

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Deadwood Formation						
HFSC-2012-010	Lawrence	NE¼ SW¼ sec. 1, T. 3 N., R. 2 E.	37.06	20.04	20.82	24.90
HFSC-2012-011	Lawrence	SE¼ SE¼ sec. 31, T. 4 N., R. 2 E.	10.71	28.05	48.00	20.82
HFSC-2012-012	Lawrence	NW¼ SE¼ sec. 8, T. 3 N., R. 3 E.	18.85	17.74	33.27	33.36
HFSC-2012-013	Lawrence	NW¼ NE¼ sec. 27, T. 3 N., R. 5 E.	2.54	51.65	37.70	18.19
HFSC-2012-020	Meade	SW¼ SW¼ sec. 32, T. 5 N., R. 5 E.	46.47	19.42	20.33	17.17
HFSC-2012-021	Meade	NE¼ SE¼ sec. 30, T. 4 N., R. 5 E.	7.90	35.44	55.64	13.21
HFSC-2012-022	Lawrence	NE¼ NE¼ sec. 16, T. 3 N., R. 5 E.	21.21	24.21	37.90	23.35
HFSC-2012-025	Meade	SW¼ SW¼ sec. 5, T. 3 N., R. 6 E.	37.66	21.34	35.61	12.40
HFSC-2012-029	Lawrence	NE¼ SW¼ sec. 23, T. 5 N., R. 3 E.	32.92	15.21	30.76	24.53
HFSC-2012-031	Pennington	NW¼ NW¼ sec. 14, T. 1 N., R. 6 E.	21.65	21.35	18.90	41.57
HFSC-2012-031-Duplicate	Pennington	NW¼ NW¼ sec. 14, T. 1 N., R. 6 E.	29.24	20.86	17.24	35.81
HFSC-2012-032	Pennington	NW¼ NW¼ sec. 10, T. 1 N., R. 6 E.	25.98	23.91	21.49	32.30
HFSC-2012-033	Pennington	NW¼ NE¼ sec. 5, T. 1 N., R. 6 E.	6.80	58.77	42.08	5.95
HFSC-2012-039	Lawrence	NW¼ SW¼ sec. 26, T. 3 N., R. 3 E.	12.46	39.04	53.41	9.34
HFSC-2012-044	Lawrence	SW¼ NE¼ sec. 21, T. 3 N., R. 5 E.	5.74	16.38	45.74	37.87
HFSC-2012-045	Lawrence	SE¼ NE¼ sec. 1, T. 3 N., R. 4 E.	2.21	8.30	51.28	40.91
HFSC-2012-046	Lawrence	SE¼ NW¼ sec. 17, T. 2 N., R. 6 E.	2.63	22.72	72.03	12.31
HFSC-2012-053	Pennington	NW¼ NE¼ sec. 13, T. 1 S., R. 6 E.	56.53	10.24	7.42	27.15
HFSC-2012-054	Pennington	NW¼ NE¼ sec. 25, T. 1 S., R. 6 E.	25.27	39.19	36.83	10.17
HFSC-2012-055	Pennington	SW¼ NW¼ sec. 13, T. 2 S., R. 6 E.	47.65	16.23	15.66	22.86
HFSC-2012-056	Pennington	SE¼ NW¼ sec. 2, T. 2 S., R. 7 E.	22.31	14.38	23.68	42.56
HFSC-2012-067	Pennington	SE¼ SW¼ sec. 25, T. 1 S., R. 6 E.	71.77	10.80	11.35	8.45
HFSC-2012-071	Custer	SE¼ NE¼ sec. 25, T. 2 S., R. 6 E.	39.13	20.65	32.50	13.26
HFSC-2013-090	Pennington	SW¼ SE¼ sec. 2, T. 2 N., R. 6 E.	12.68	27.29	55.55	14.52
HFSC-2013-096	Custer	SE¼ NW¼ sec. 27, T. 3 S., R. 3 E.	51.17	21.95	14.93	15.33
HFSC-2013-097	Custer	NW¼ SE¼ sec. 34, T. 3 S., R. 3 E.	1.29	23.12	59.62	23.24
HFSC-2013-098	Custer	NW¼ NW¼ sec. 15, T. 3 S., R. 3 E.	5.68	31.10	47.74	24.26
HFSC-2013-099	Custer	NE¼ NW¼ sec. 3, T. 3 S., R. 3 E.	2.39	30.44	43.42	31.77
HFSC-2013-101	Pennington	SE¼ NE¼ sec. 23, T. 1 S., R. 2 E.	13.81	40.27	38.41	14.87
HFSC-2013-102	Pennington	NE¼ NE¼ sec. 11, T. 1 S., R. 2 E.	8.16	28.60	49.72	21.12
HFSC-2013-103	Pennington	SW¼ NW¼ sec. 35, T. 1 N., R. 2 E.	62.28	14.16	8.68	16.60
HFSC-2013-104	Pennington	NE¼ SE¼ sec. 36, T. 2 N., R. 1 E.	36.13	26.75	13.50	26.75
HFSC-2013-105	Pennington	NW¼ NW¼ sec. 5, T. 1 N., R. 2 E.	49.37	17.64	13.68	21.76
HFSC-2013-107	Pennington	SW¼ SE¼ sec. 15, T. 1 N., R. 2 E.	63.42	15.06	7.88	15.50
HFSC-2013-108	Pennington	SE¼ NE¼ sec. 27, T. 1 S., R. 3 E.	66.73	16.78	11.15	7.80
HFSC-2013-109	Pennington	NE¼ SW¼ sec. 12, T. 1 N., R. 2 E.	49.80	14.50	10.13	27.56

Sample number	County	Location	Percent retained on 16 sieve	Percent retained on 20/40 sieves	Percent retained on 40/70 sieves	Percent retained on 100 and finer sieves
Deadwood Formation - continued						
HFSC-2013-110	Pennington	NW¼ NW¼ sec. 1, T. 1 N., R. 2 E.	24.80	18.11	13.54	45.84
HFSC-2013-147	Custer	NE¼ SW¼ sec. 32, T. 5 S., R. 5 E.	34.80	22.79	26.80	20.02
HFSC-2013-147-Duplicate	Custer	NE¼ SW¼ sec. 32, T. 5 S., R. 5 E.	31.10	21.34	29.57	22.46
HFSC-2013-149	Custer	SE¼ SE¼ sec. 33, T. 4 S., R. 4 E.	15.03	32.27	44.93	17.16
HFSC-2013-150	Custer	SE¼ NW¼ sec. 15, T. 5 S., R. 4 E.	5.14	7.85	27.85	60.86
HFSC-2013-179	Pennington	NE¼ SW¼ sec. 15, T. 2 N., R. 2 E.	9.47	15.56	41.64	36.23
HFSC-2013-179-Duplicate	Pennington	NE¼ SW¼ sec. 15, T. 2 N., R. 2 E.	11.05	14.97	40.68	36.27
HFSC-2013-180	Lawrence	SE¼ SW¼ sec. 3, T. 2 N., R. 2 E.	11.31	16.12	33.33	42.24
Minnelusa Formation						
HFSC-2012-003	Lawrence	NW¼ SE¼ sec. 1, T. 5 N., R. 1 E.	0.05	8.27	16.89	77.02
HFSC-2012-004	Lawrence	SE¼ SE¼ sec. 31, T. 6 N., R. 1 E.	53.35	18.78	9.38	20.56
HFSC-2012-005	Lawrence	NW¼ NE¼ sec. 2, T. 5 N., R. 3 E.	22.67	15.62	10.13	53.48
HFSC-2012-008	Lawrence	SW¼ NE¼ sec. 31, T. 3 N., R. 1 E.	42.98	14.99	8.77	34.96
HFSC-2012-018	Lawrence	SW¼ NW¼ sec. 31, T. 6 N., R. 3 E.	0.00	0.98	7.78	91.77
HFSC-2012-019	Meade	NE¼ NE¼ sec. 28, T. 5 N., R. 5 E.	7.63	21.79	19.01	54.83
HFSC-2012-023	Meade	SW¼ SE¼ sec. 26, T. 3 N., R. 6 E.	0.22	12.24	16.97	72.86
HFSC-2012-024	Meade	NW¼ SW¼ sec. 5, T. 3 N., R. 6 E.	0.03	8.92	18.65	74.76
HFSC-2012-026	Meade	NW¼ SW¼ sec. 30, T. 4 N., R. 6 E.	1.44	9.42	11.03	79.48
HFSC-2012-027	Meade	NE¼ SW¼ sec. 7, T. 5 N., R. 5 E.	1.80	16.98	14.66	69.31
HFSC-2012-028	Lawrence	SW¼ SW¼ sec. 15, T. 5 N., R. 4 E.	0.14	3.64	21.46	75.80
HFSC-2012-030	Pennington	NW¼ NW¼ sec. 18, T. 1 N., R. 7 E.	0.01	6.84	12.79	82.59
HFSC-2012-052	Pennington	NE¼ SW¼ sec. 9, T. 1 S., R. 7 E.	1.26	4.41	11.26	83.71
HFSC-2012-052-Duplicate	Pennington	NE¼ SW¼ sec. 9, T. 1 S., R. 7 E.	0.97	3.47	11.28	84.82
HFSC-2012-057	Pennington	NE¼ SE¼ sec. 7, T. 2 S., R. 7 E.	15.19	21.98	13.99	51.51
HFSC-2012-066	Pennington	SE¼ SW¼ sec. 20, T. 1 S., R. 7 E.	0.08	5.11	10.66	85.30
HFSC-2012-069	Custer	NW¼ SW¼ sec. 19, T. 3 S., R. 7 E.	20.73	9.44	18.03	53.00
HFSC-2012-072	Custer	NW¼ SW¼ sec. 32, T. 2 S., R. 7 E.	32.72	13.66	9.93	45.30
HFSC-2013-074	Pennington	SE¼ SW¼ sec. 17, T. 2 S., R. 7 E.	48.56	15.63	9.53	28.04
HFSC-2013-091	Custer	SW¼ SW¼ sec. 1, T. 4 S., R. 1 E.	48.29	15.07	9.73	28.70
HFSC-2013-092	Custer	NW¼ NW¼ sec. 8, T. 4 S., R. 2 E.	2.72	21.28	18.26	61.66
HFSC-2013-093	Custer	SW¼ SW¼ sec. 9, T. 4 S., R. 2 E.	41.77	14.35	11.76	33.98
HFSC-2013-094	Custer	SE¼ SE¼ sec. 4, T. 4 S., R. 2 E.	54.67	15.88	7.70	23.56
HFSC-2013-100	Pennington	NW¼ NW¼ sec. 35, T. 1 S., R. 2 E.	0.01	1.46	17.17	82.27
HFSC-2013-111	Custer	NW¼ NW¼ sec. 31, T. 3 S., R. 2 E.	0.12	7.13	14.69	80.04
HFSC-2013-138	Custer	SW¼ NE¼ sec. 26, T. 5 S., R. 4 E.	9.95	16.15	16.60	59.60

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Minnelusa Formation - continued						
HFSC-2013-139	Custer	NW¼ NW¼ sec. 9, T. 6 S., R. 4 E.	0.93	7.32	30.81	62.50
HFSC-2013-140	Custer	NW¼ NE¼ sec. 23, T. 6 S., R. 4 E.	0.36	7.65	30.30	64.17
HFSC-2013-141	Custer	SE¼ SW¼ sec. 29, T. 6 S., R. 5 E.	0.25	6.68	24.66	69.92
HFSC-2013-142	Custer	NE¼ NE¼ sec. 4, T. 7 S., R. 5 E.	0.00	1.07	21.02	78.36
HFSC-2013-143	Custer	NW¼ NE¼ sec. 29, T. 6 S., R. 5 E.	0.04	7.25	37.70	57.65
HFSC-2013-144	Custer	SW¼ SW¼ sec. 19, T. 6 S., R. 5 E.	19.19	12.90	12.52	57.36
HFSC-2013-145	Custer	NE¼ NW¼ sec. 20, T. 6 S., R. 5 E.	33.00	14.27	15.97	38.84
HFSC-2013-146	Custer	NW¼ NW¼ sec. 20, T. 6 S., R. 5 E.	4.89	16.91	15.59	65.46
HFSC-2013-148	Custer	NW¼ SW¼ sec. 25, T. 5 S., R. 4 E.	0.27	9.30	61.26	34.01
HFSC-2013-148-Duplicate	Custer	NW¼ SW¼ sec. 25, T. 5 S., R. 4 E.	0.35	9.83	62.07	32.74
HFSC-2013-151	Custer	NE¼ SW¼ sec. 32, T. 5 S., R. 4 E.	26.30	16.49	12.63	46.68
HFSC-2013-152	Custer	NW¼ NE¼ sec. 30, T. 5 S., R. 4 E.	58.92	13.87	6.77	21.97
HFSC-2013-153	Custer	SE¼ NE¼ sec. 35, T. 5 S., R. 3 E.	0.00	0.34	15.68	84.13
HFSC-2013-154	Custer	SE¼ SE¼ sec. 27, T. 5 S., R. 3 E.	27.31	13.01	18.35	43.22
HFSC-2013-155	Custer	SW¼ SW¼ sec. 2, T. 5 S., R. 3 E.	0.11	2.26	5.55	92.49
HFSC-2013-156	Custer	NE¼ SW¼ sec. 20, T. 4 S., R. 3 E.	24.57	17.68	10.12	49.66
HFSC-2013-157	Custer	NW¼ SE¼ sec. 29, T. 4 S., R. 3 E.	0.02	6.55	18.61	76.53
HFSC-2013-158	Custer	SW¼ NW¼ sec. 7, T. 5 S., R. 3 E.	0.01	3.14	12.78	85.01
HFSC-2013-159	Custer	NE¼ SW¼ sec. 14, T. 5 S., R. 2 E.	0.00	1.19	8.35	91.25
HFSC-2013-160	Custer	SE¼ SW¼ sec. 31, T. 4 S., R. 2 E.	0.04	1.29	34.90	64.24
HFSC-2013-161	Custer	SE¼ SW¼ sec. 22, T. 3 S., R. 2 E.	39.38	14.76	8.33	39.21
HFSC-2013-162	Custer	NW¼ SW¼ sec. 8, T. 3 S., R. 1 E.	5.23	14.72	13.38	68.59
HFSC-2013-163	Custer	SW¼ SW¼ sec. 33, T. 2 S., R. 1 E.	23.29	12.44	9.89	56.30
HFSC-2013-164	Custer	SE¼ NE¼ sec. 20, T. 2 S., R. 1 E.	0.22	9.87	8.35	83.63
HFSC-2013-165	Pennington	SW¼ NE¼ sec. 8, T. 2 S., R. 1 E.	1.70	11.58	10.19	78.17
HFSC-2013-166	Pennington	SW¼ SW¼ sec. 10, T. 2 S., R. 1 E.	42.00	13.17	18.64	28.16
HFSC-2013-167	Pennington	SE¼ SW¼ sec. 12, T. 2 S., R. 1 E.	40.75	14.41	6.50	39.93
HFSC-2013-168	Custer	NW¼ SE¼ sec. 31, T. 2 S., R. 2 E.	3.92	8.83	26.94	62.86
HFSC-2013-169	Custer	NE¼ NE¼ sec. 16, T. 3 S., R. 2 E.	14.26	19.17	12.77	56.36
HFSC-2013-170	Custer	NE¼ NW¼ sec. 28, T. 3 S., R. 2 E.	0.70	10.21	10.90	80.14
HFSC-2013-170-Duplicate	Custer	NE¼ NW¼ sec. 28, T. 3 S., R. 2 E.	0.12	8.31	11.64	82.15
HFSC-2013-171	Custer	NW¼ NW¼ sec. 3, T. 3 S., R. 1 E.	0.27	4.18	30.49	66.71
HFSC-2013-172	Custer	SE¼ SE¼ sec. 4, T. 3 S., R. 1 E.	0.00	7.16	48.78	49.96
HFSC-2013-173	Pennington	NE¼ SE¼ sec. 20, T. 1 S., R. 2 E.	0.11	4.25	19.59	77.66
HFSC-2013-174	Pennington	SW¼ NE¼ sec. 19, T. 1 S., R. 2 E.	0.23	2.74	18.92	78.80
HFSC-2013-175	Pennington	SE¼ NW¼ sec. 26, T. 1 S., R. 1 E.	43.58	17.03	8.63	32.86

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Minnelusa Formation - continued						
HFSC-2013-176	Pennington	SE¼ SW¼ sec. 28, T. 1 S., R. 1 E.	6.38	16.03	11.86	68.01
HFSC-2013-177	Pennington	SW¼ SW¼ sec. 16, T. 1 S., R. 1 E.	5.74	16.99	19.69	59.34
HFSC-2013-178	Pennington	SW¼ NE¼ sec. 36, T. 1 N., R. 1 E.	26.25	12.10	7.73	55.44
Hulett Sandstone Member of the Sundance Formation						
HFSC-2012-002	Lawrence	NE¼ SW¼ sec. 11, T. 6 N., R. 2 E.	21.15	15.47	9.58	55.96
HFSC-2012-043	Pennington	NE¼ NE¼ sec. 17, T. 2 N., R. 7 E.	51.76	14.44	8.45	27.13
HFSC-2012-051	Pennington	SE¼ SW¼ sec. 34, T. 1 N., R. 7 E.	0.21	14.73	13.27	74.52
HFSC-2012-061	Pennington	SW¼ SE¼ sec. 22, T. 1 N., R. 7 E.	42.33	17.84	9.18	32.66
HFSC-2012-063	Pennington	NW¼ NW¼ sec. 11, T. 1 S., R. 7 E.	0.12	11.00	15.67	75.99
HFSC-2013-075	Custer	SW¼ SW¼ sec. 3, T. 3 S., R. 7 E.	59.05	12.92	6.60	22.94
HFSC-2013-075-Duplicate	Custer	SW¼ SW¼ sec. 3, T. 3 S., R. 7 E.	56.68	14.19	7.34	23.46
HFSC-2013-077	Custer	NE¼ SW¼ sec. 5, T. 4 S., R. 7 E.	40.58	18.11	8.68	34.66
HFSC-2013-123	Fall River	NE¼ NE¼ sec. 20, T. 7 S., R. 3 E.	4.28	11.26	10.62	75.70
HFSC-2013-124	Fall River	NW¼ NW¼ sec. 7, T. 7 S., R. 3 E.	2.65	9.67	11.64	78.09
HFSC-2013-130	Fall River	NW¼ NE¼ sec. 2, T. 7 S., R. 2 E.	0.02	4.08	10.49	86.81
HFSC-2013-131	Custer	SE¼ SW¼ sec. 9, T. 6 S., R. 2 E.	8.74	11.24	13.14	68.99
HFSC-2013-132	Custer	SW¼ NE¼ sec. 10, T. 6 S., R. 1 E.	0.30	8.13	11.68	81.95
HFSC-2013-137	Custer	NW¼ NW¼ sec. 35, T. 6 S., R. 2 E.	0.37	7.76	9.44	84.09
Unkpapa Sandstone						
HFSC-2012-038	Meade	NE¼ NE¼ sec. 25, T. 3 N., R. 6 E.	0.02	4.78	11.73	85.03
HFSC-2012-058	Custer	NE¼ NW¼ sec. 35, T. 2 S., R. 7 E.	1.62	8.48	8.28	83.01
HFSC-2012-062	Pennington	SW¼ SE¼ sec. 22, T. 1 N., R. 6 E.	1.44	4.84	4.85	89.64
HFSC-2013-086	Fall River	NE¼ NW¼ sec. 26, T. 8 S., R. 5 E.	0.00	1.09	2.23	96.97
HFSC-2013-202*	Pennington	SW¼ SW¼ sec. 23, T. 2 N., R. 7 E.	0.01	0.96	5.71	93.61
HFSC-2013-208*	Pennington	NE¼ NE¼ sec. 34, T. 2 N., R. 7 E.	0.02	2.99	6.46	91.34
Lakota Formation						
HFSC-2012-001	Butte	SE¼ NW¼ sec. 3, T. 7 N., R. 2 E.	0.09	1.18	3.38	95.64
HFSC-2012-006	Lawrence	SW¼ SW¼ sec. 21, T. 6 N., R. 4 E.	0.00	1.26	35.59	63.77
HFSC-2012-007	Meade	SE¼ SW¼ sec. 3, T. 5 N., R. 5 E.	0.62	20.93	66.63	18.53
HFSC-2012-016	Lawrence	SW¼ NW¼ sec. 30, T. 6 N., R. 5 E.	0.73	6.68	15.21	78.57
HFSC-2012-035	Meade	NW¼ NE¼ sec. 29, T. 3 N., R. 7 E.	0.02	1.41	32.63	66.41
HFSC-2012-036	Meade	NW¼ NW¼ sec. 36, T. 4 N., R. 6 E.	0.34	2.85	52.02	45.90
HFSC-2012-037	Meade	NE¼ NW¼ sec. 18, T. 3 N., R. 7 E.	0.19	2.64	3.20	94.49

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Lakota Formation - continued						
HFSC-2012-040	Lawrence	NW¼ NE¼ sec. 3. T. 6 N., R. 3 E.	22.86	16.57	11.71	51.23
HFSC-2012-041	Lawrence	NW¼ NE¼ sec. 7. T. 7 N., R. 3 E.	0.00	2.56	54.00	45.32
HFSC-2012-042	Lawrence	SW¼ SW¼ sec. 17. T. 7 N., R. 3 E.	9.81	8.28	19.90	63.30
HFSC-2012-059	Custer	SE¼ SE¼ sec. 35. T. 2 S., R. 7 E.	6.23	9.16	7.18	78.83
HFSC-2012-065	Pennington	SW¼ SE¼ sec. 12. T. 1 S., R. 7 E.	0.17	4.28	5.55	90.97
HFSC-2012-068	Pennington	SW¼ NE¼ sec. 26. T. 2 N., R. 7 E.	0.00	0.30	15.23	84.61
HFSC-2012-068-Duplicate	Pennington	SW¼ NE¼ sec. 26. T. 2 N., R. 7 E.	0.00	0.52	16.09	83.61
HFSC-2013-078	Custer	SW¼ SW¼ sec. 4. T. 4 S., R. 7 E.	0.04	3.92	5.78	91.18
HFSC-2013-083	Fall River	NW¼ SW¼ sec. 29. T. 7 S., R. 6 E.	11.62	12.60	15.02	62.72
HFSC-2013-085	Fall River	SW¼ NW¼ sec. 25. T. 8 S., R. 5 E.	0.00	4.15	10.68	86.76
HFSC-2013-087	Fall River	NW¼ SW¼ sec. 20. T. 8 S., R. 5 E.	1.01	7.09	7.07	86.12
HFSC-2013-112	Fall River	NW¼ NE¼ sec. 36. T. 7 S., R. 3 E.	0.01	1.51	1.86	96.98
HFSC-2013-113	Fall River	NE¼ SE¼ sec. 2. T. 8 S., R. 3 E.	0.00	0.71	3.61	95.88
HFSC-2013-117	Fall River	SW¼ NE¼ sec. 35. T. 8 S., R. 3 E.	13.37	10.03	8.17	69.74
HFSC-2013-121	Fall River	NE¼ SE¼ sec. 29. T. 7 S., R. 3 E.	0.01	1.59	2.97	95.93
HFSC-2013-125	Fall River	NE¼ NE¼ sec. 14. T. 7 S., R. 2 E.	2.12	12.09	8.81	78.91
HFSC-2013-126	Fall River	NE¼ SE¼ sec. 14. T. 7 S., R. 2 E.	0.01	2.33	40.61	58.29
HFSC-2013-133	Custer	SW¼ SW¼ sec. 10. T. 6 S., R. 1 E.	7.96	8.74	53.19	32.53
HFSC-2013-135	Fall River	NW¼ NE¼ sec. 4. T. 7 S., R. 2 E.	0.09	0.86	1.90	97.37
HFSC-2013-136	Fall River	SW¼ SW¼ sec. 3. T. 7 S., R. 2 E.	17.81	9.93	38.71	36.04
HFSC-2013-136-Duplicate	Fall River	SW¼ SW¼ sec. 3. T. 7 S., R. 2 E.	16.46	9.23	39.36	37.37
HFSC-2013-214*	Meade	SW¼ SW¼ sec. 19, T. 6 N., R. 5 E.	0.13	0.35	33.16	66.56
HFSC-2013-217*	Meade	SE¼ NE¼ sec. 31, T. 5 N., R. 6 E.	0.02	5.37	83.97	14.69
Fall River Sandstone						
HFSC-2012-015	Meade	SE¼ SE¼ sec. 19. T. 6 N., R. 5 E.	0.10	2.22	65.98	32.36
HFSC-2012-017	Lawrence	SW¼ NW¼ sec. 11. T. 6 N., R. 4 E.	1.17	16.16	38.45	48.19
HFSC-2012-047	Pennington	NW¼ NE¼ sec. 26. T. 2 N., R. 7 E.	0.70	9.90	38.99	52.97
HFSC-2012-048	Pennington	NE¼ SE¼ sec. 23. T. 2 N., R. 7 E.	1.55	7.42	44.20	49.42
HFSC-2012-049	Pennington	SW¼ SE¼ sec. 11. T. 1 N., R. 7 E.	0.49	14.94	9.82	77.35
HFSC-2012-060	Custer	NW¼ SE¼ sec. 36. T. 2 S., R. 7 E.	0.03	3.62	6.79	90.53
HFSC-2012-064	Pennington	NW¼ NW¼ sec. 18. T. 1 S., R. 8 E.	0.97	9.00	7.82	83.76
HFSC-2013-076	Custer	SW¼ SE¼ sec. 4. T. 4 S., R. 7 E.	54.52	12.86	13.72	20.54
HFSC-2013-079	Fall River	NW¼ NE¼ sec. 33. T. 7 S., R. 6 E.	6.86	7.81	28.79	57.79
HFSC-2013-080	Fall River	NE¼ NW¼ sec. 33. T. 7 S., R. 6 E.	25.86	7.85	26.25	41.30
HFSC-2013-084	Fall River	NE¼ SE¼ sec. 25. T. 8 S., R. 5 E.	0.06	3.04	7.58	90.13

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Fall River Sandstone - continued						
HFSC-2013-089	Fall River	SW¼ SW¼ sec. 20. T. 8 S., R. 5 E.	26.71	14.43	13.56	47.14
HFSC-2013-114	Fall River	NW¼ NW¼ sec. 26. T. 8 S., R. 3 E.	0.04	2.01	2.70	95.71
HFSC-2013-115	Fall River	SW¼ NE¼ sec. 16. T. 9 S., R. 4 E.	24.00	9.71	7.50	60.01
HFSC-2013-116	Fall River	NE¼ NW¼ sec. 7. T. 9 S., R. 4 E.	25.47	9.43	19.72	46.87
HFSC-2013-119	Fall River	NW¼ NW¼ sec. 3. T. 9 S., R. 3 E.	0.39	11.59	31.88	59.88
HFSC-2013-120	Fall River	NW¼ NW¼ sec. 17. T. 8 S., R. 3 E.	2.08	4.55	5.99	88.09
HFSC-2013-127	Fall River	NE¼ NW¼ sec. 25. T. 7 S., R. 2 E.	40.32	10.49	11.93	38.65
HFSC-2013-128	Fall River	SE¼ NW¼ sec. 36. T. 7 S., R. 2 E.	0.01	1.35	73.72	25.78
HFSC-2013-129	Fall River	SE¼ NE¼ sec. 3. T. 8 S., R. 2 E.	0.14	4.06	4.05	92.59
HFSC-2013-134	Custer	NW¼ NW¼ sec. 16. T. 6 S., R. 1 E.	22.97	11.70	7.65	59.10
Lakota Formation - Fall River Sandstone						
HFSC-2012-014	Meade	SW¼ SE¼ sec. 31. T. 5 N., R. 6 E.	0.40	2.71	7.74	89.84
Fox Hills Sandstone						
HFSC-2013-181	Butte	NE¼ SE¼ sec. 23. T. 12 N., R. 5 E.	11.89	12.41	9.32	68.23
HFSC-2013-182	Butte	SE¼ SE¼ sec. 13. T. 12 N., R. 5 E.	27.24	16.05	20.26	39.33
HFSC-2013-183	Butte	SE¼ SE¼ sec. 1. T. 12 N., R. 5 E.	33.31	16.66	13.54	39.24
HFSC-2013-184	Butte	SE¼ SE¼ sec. 29. T. 14 N., R. 6 E.	0.79	2.00	3.00	94.65
HFSC-2013-185	Butte	NE¼ NE¼ sec. 20. T. 14 N., R. 6 E.	0.03	0.38	0.68	98.98
HFSC-2013-185-Duplicate	Butte	NE¼ NE¼ sec. 20. T. 14 N., R. 6 E.	0.05	0.42	0.73	98.88
HFSC-2013-186	Butte	SE¼ SE¼ sec. 9. T. 14 N., R. 6 E.	0.89	6.44	8.95	85.11
HFSC-2013-186-Duplicate	Butte	SE¼ SE¼ sec. 9. T. 14 N., R. 6 E.	1.37	6.43	7.71	85.75
HFSC-2013-187	Butte	SE¼ SE¼ sec. 1. T. 14 N., R. 5 E.	4.35	8.07	5.32	83.38
HFSC-2013-188	Butte	SE¼ SE¼ sec. 4. T. 14 N., R. 5 E.	13.50	14.47	8.51	65.43
HFSC-2013-189	Harding	SE¼ SE¼ sec. 31. T. 16 N., R. 3 E.	0.16	6.81	10.00	84.84
HFSC-2013-190	Harding	SW¼ SW¼ sec. 31. T. 16 N., R. 3 E.	2.98	25.52	21.70	54.74
HFSC-2013-191	Harding	NE¼ NW¼ sec. 25. T. 16 N., R. 2 E.	0.02	1.37	14.97	84.21
HFSC-2013-192	Harding	SW¼ SE¼ sec. 22. T. 16 N., R. 2 E.	0.24	8.91	11.70	81.32
HFSC-2013-193	Harding	SW¼ NW¼ sec. 14. T. 16 N., R. 1 E.	2.58	10.77	20.63	68.52
HFSC-2013-194	Carter, MT	NW¼ NW¼ sec. 2. T. 5 S., R. 62 E.	0.27	15.10	13.48	74.22
HFSC-2013-195	Butte	SE¼ SE¼ sec. 33. T. 14 N., R. 7 E.	5.38	16.80	10.74	69.48
HFSC-2013-196	Butte	SW¼ SW¼ sec. 35. T. 14 N., R. 7 E.	0.54	4.35	3.32	92.48
HFSC-2013-197	Butte	NW¼ SW¼ sec. 25. T. 13 N., R. 7 E.	0.08	2.46	5.03	93.11
HFSC-2013-198	Butte	NE¼ SW¼ sec. 35. T. 13 N., R. 7 E.	0.12	10.88	12.66	78.87
HFSC-2013-199	Butte	NW¼ SE¼ sec. 22. T. 12 N., R. 7 E.	0.14	4.85	8.72	87.51

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Fox Hills Sandstone - continued						
HFSC-2013-200	Butte	NW¼ SE¼ sec. 34. T. 12 N., R. 8 E.	3.71	13.18	9.74	75.44
HFSC-2013-240	Meade	SE¼ SE¼ sec. 9. T. 7 N., R. 12 E.	0.46	12.07	12.18	77.80
HFSC-2013-241	Meade	SW¼ NW¼ sec. 20. T. 12 N., R. 13 E.	55.65	17.37	8.23	20.72
HFSC-2013-242	Meade	NW¼ NE¼ sec. 36. T. 7 N., R. 13 E.	0.82	8.52	15.13	77.48
HFSC-2013-243	Meade	SE¼ NE¼ sec. 23. T. 8 N., R. 11 E.	0.06	13.74	26.16	64.72
HFSC-2013-244	Meade	SW¼ SE¼ sec. 12. T. 9 N., R. 11 E.	0.88	13.73	13.44	74.68
HFSC-2013-245	Meade	NW¼ NW¼ sec. 22. T. 10 N., R. 11 E.	0.13	6.84	12.06	82.91
HFSC-2013-246	Meade	NE¼ NE¼ sec. 4. T. 10 N., R. 13 E.	4.13	18.24	16.93	64.00
HFSC-2013-247	Meade	SE¼ SE¼ sec. 1. T. 10 N., R. 16 E.	0.08	1.99	6.20	92.40
HFSC-2013-248	Meade	NE¼ NW¼ sec. 22. T. 10 N., R. 14 E.	25.00	12.04	11.47	53.36
HFSC-2013-249	Meade	SW¼ SW¼ sec. 26. T. 9 N., R. 14 E.	71.29	12.80	5.33	11.97
HFSC-2013-250	Butte	SE¼ SE¼ sec. 6. T. 11 N., R. 9 E.	0.17	13.74	12.75	76.31
HFSC-2013-251	Meade	SW¼ SW¼ sec. 16. T. 12 N., R. 10 E.	0.03	0.38	1.24	98.44
HFSC-2013-252	Meade	NW¼ SW¼ sec. 2. T. 11 N., R. 10 E.	0.32	5.15	6.86	88.69
HFSC-2013-253	Meade	SW¼ NW¼ sec. 35. T. 12 N., R. 10 E.	0.03	1.61	2.10	96.65
HFSC-2013-254	Perkins	SW¼ NE¼ sec. 16. T. 13 N., R. 10 E.	0.59	20.97	21.79	60.75
HFSC-2013-255	Meade	NW¼ SE¼ sec. 15. T. 12 N., R. 11 E.	0.01	5.72	12.95	83.23
HFSC-2013-257	Meade	SW¼ SW¼ sec. 21. T. 8 N., R. 13 E.	63.39	16.60	8.58	13.45
White River Group						
HFSC-2013-206*	Tripp	SE¼ SE¼ sec. 20, T. 95 N., R. 78 W.	11.95	44.98	20.91	27.57
HFSC-2013-218*	Meade	NE¼ SE¼ sec. 8. T. 12 N., R. 13 E.	13.4	65.00	23.35	6.05
Arikaree Group						
HFSC-2013-229	Bennett	NW¼ sec. 17, T. 36 N., R. 33 W.	3.70	12.17	18.73	67.36
HFSC-2013-236	Bennett	SE¼ SW¼ sec. 21, T. 39 N., R. 37 W.	0.35	2.68	23.38	74.71
HFSC-2013-237	Bennett	SE¼ SE¼ sec. 16, T. 38 N., R. 37 W.	0.01	0.22	0.60	99.23
HFSC-2013-238	Bennett	NE¼ NW¼ sec. 2, T. 38 N., R. 40 W.	0.01	1.21	4.76	94.65
HFSC-2013-239	Bennett	SW¼ sec. 8, T. 38 N., R. 38 W.	0.18	2.20	1.22	96.70
Ogallala Group						
HFSC-2013-207*	Gregory	SE¼ NE¼ sec. 26, T. 97 N., R. 72 W.	15.74	44.03	18.07	2.21
HFSC-2013-210*	Charles Mix	SE¼ SW¼ sec. 36, T. 96 N., R. 65 W.	29.79	45.82	29.58	3.57
HFSC-2013-219*	Gregory	NE¼ NE¼ sec. 21, T. 97 N., R. 72 W.	12.68	50.87	45.63	3.79
HFSC-2013-226	Bennett	NW¼ sec. 5, T. 37 N., R. 33 W.	0.58	3.58	32.07	64.65
HFSC-2013-227	Bennett	SW¼ NW¼ sec. 8, T. 37 N., R. 34 W.	0.64	16.76	52.60	37.68

Sample number	County	Location	Percent retained on			
			16 sieve	20/40 sieves	40/70 sieves	100 and finer sieves
Ogallala Group - continued						
HFSC-2013-228	Bennett	NW¼ sec. 17, T. 36 N., R. 33 W.	0.06	5.02	40.57	57.40
HFSC-2013-233	Bennett	SE¼ SE¼ sec. 24, T. 39 N., R. 36 W.	0.07	7.89	8.41	85.72
HFSC-2013-234	Bennett	SE¼ NE¼ sec. 17, T. 38 N., R. 36 W.	0.51	12.80	28.65	61.35
Outwash, valley train						
HFSC-2013-203*	Douglas	NE¼ SE¼ sec. 36, T. 98 N., R. 63 W.	49.41	34.1	17.31	3.81
Terrace deposits						
HFSC-2013-204*	Stanley	NE¼ SW¼ sec. 14, T. 5 N., R. 30 E.	5.39	62.98	35.61	8.26
HFSC-2013-205*	Mellette	SW¼ SW¼ sec. 27, T. 41 N., R. 27 W.	74.47	13.83	6.76	6.67
HFSC-2013-211*	Mellette	SW¼ NW¼ sec.12, T. 42, N., R. 29 W.	15.99	40.44	38.51	13.97
HFSC-2013-215*	Lyman	NW¼ NW¼ sec. 5, T. 107 N., R. 14 W.	50.41	40.01	8.71	3.02
HFSC-2013-216*	Fall River	SE¼ SW¼ sec. 34, T. 7 S., R. 6 E.	36.78	43.35	19.89	5.59
HFSC-2013-224*	Meade	SE¼ NE¼ sec. 31, T. 7 N., R. 5 E.	35.97	42.09	20.33	7.92
Sand Hills Formation						
HFSC-2013-230	Bennett	SE¼ NW¼ sec. 7, T. 35 N., R. 35 W.	0.01	3.18	62.34	36.74
HFSC-2013-230-Duplicate	Bennett	SE¼ NW¼ sec. 7, T. 35 N., R. 35 W.	0.02	3.55	63.18	35.76
HFSC-2013-231	Bennett	SE¼ NE¼ sec. 19, T. 36 N., R. 37 W.	0.00	1.12	45.14	54.60
HFSC-2013-232	Bennett	SE¼ SW¼ sec. 8, T. 35 N., R. 37 W.	0.04	0.79	38.72	61.08
Alluvium						
HFSC-2013-209*	Meade	SE¼ NE¼ sec. 14, T. 10 N., R. 14 E.	41.65	27.5	15.45	18.16
HFSC-2013-220*	Buffalo	SW¼ SW¼ sec. 13, T. 106 N., R. 71 E.	9.74	58.74	46.89	1.65
HFSC-2013-222*	Meade	NW¼ NW¼ sec. 8, T. 3 N., R. 7 E.	20.65	29.91	32.19	22.93
Unknown						
HFSC-2013-201*	Adams, ND	NE¼ SW¼ sec. 15, T. 129 N., R. 98 W.	26.33	41.52	26.91	11.53
HFSC-2013-212*	Mellette	NE¼ NW¼ sec. 36, T. 43 N., R. 26 W.	9.26	36.72	43.41	20.73
HFSC-2013-213*	Pennington	NW¼ NE¼ sec. 24, T. 2 N., R. 8 E.	0.33	22.06	57.78	29.03
HFSC-2013-221*	Stanley	SW¼ SW¼ sec. 4, T. 4 N., R. 31 E.	12.48	56.18	36.18	11.48
HFSC-2013-223*	Jackson	NE¼ NW¼ sec. 5, T. 43 N., R. 35 W.	26.5	39.28	23.32	15.96
HFSC-2013-225*	Jackson	NE¼ NW¼ sec. 5, T. 43 N., R. 35 W.	13.68	59.61	34.98	4.34

* Sample was collected by a private individual