Frac Sand Potential on Selected SITLA Lands in Utah

by

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INTRODUCTION

This open-file report provides a reconnaissance-level summary of frac sand potential in Utah. The report was originally commissioned by the Utah School and Institutional Trust Lands Administration (SITLA) to assess frac sand potential on SITLA lands. The report was completed in 2013. Beyond providing data on frac sand potential, the report provides general data on sand and sandstone deposits in Utah that may indicate suitability for other applications that require high-silica sand. The original contract-deliverable report is provided “as is,” and no updates have been made to the text or figures.

Frac sand is a proppant used in the oil and gas industry. During the hydraulic fracturing process, small fractures are created in oil and gas reservoirs and proppant is pumped into the fractures to keep them open, allowing for better flow of oil and gas into the wellbore. Frac sand is mined domestically in several states, but frac sand sourced near its end use has significant economic advantages. Frac sand is primarily sourced from quartz-rich sand and sandstone deposits and has a fairly stringent set of specifications. Since the 2013 completion of this report, a trend in the oil and gas industry has been to use more proppant in hydraulically fractured wells, and frac sand specifications have loosened. This opened up more deposits to consideration for use. Also, a variety of frac sand-related activity has occurred in Utah over the past decade or so. Explorers have evaluated frac sand in a variety of places including southwest Utah, western Utah, the San Rafael Swell, and the Uinta Basin. Because the Uinta Basin is an actively producing oil and gas basin, it is the obvious target for frac sand exploration. Frac sand was first produced in Utah in 2019 along the northeast edge of the Uinta Basin north of Vernal. At their RHEX mine, Ramsey Hill Exploration began producing frac sand from unconsolidated Quaternary-age mixed alluvial and eolian deposits and over the years the mine proceeded into the Triassic-Jurassic age Nugget Sandstone, a unit the UGS sampled during this reconnaissance study (Figure I1). The RHEX mine can produce 40/70 and 100 mesh products and has a production capacity of 3 million (short?) tons of frac sand per year (Ramsey Hill Exploration, undated).

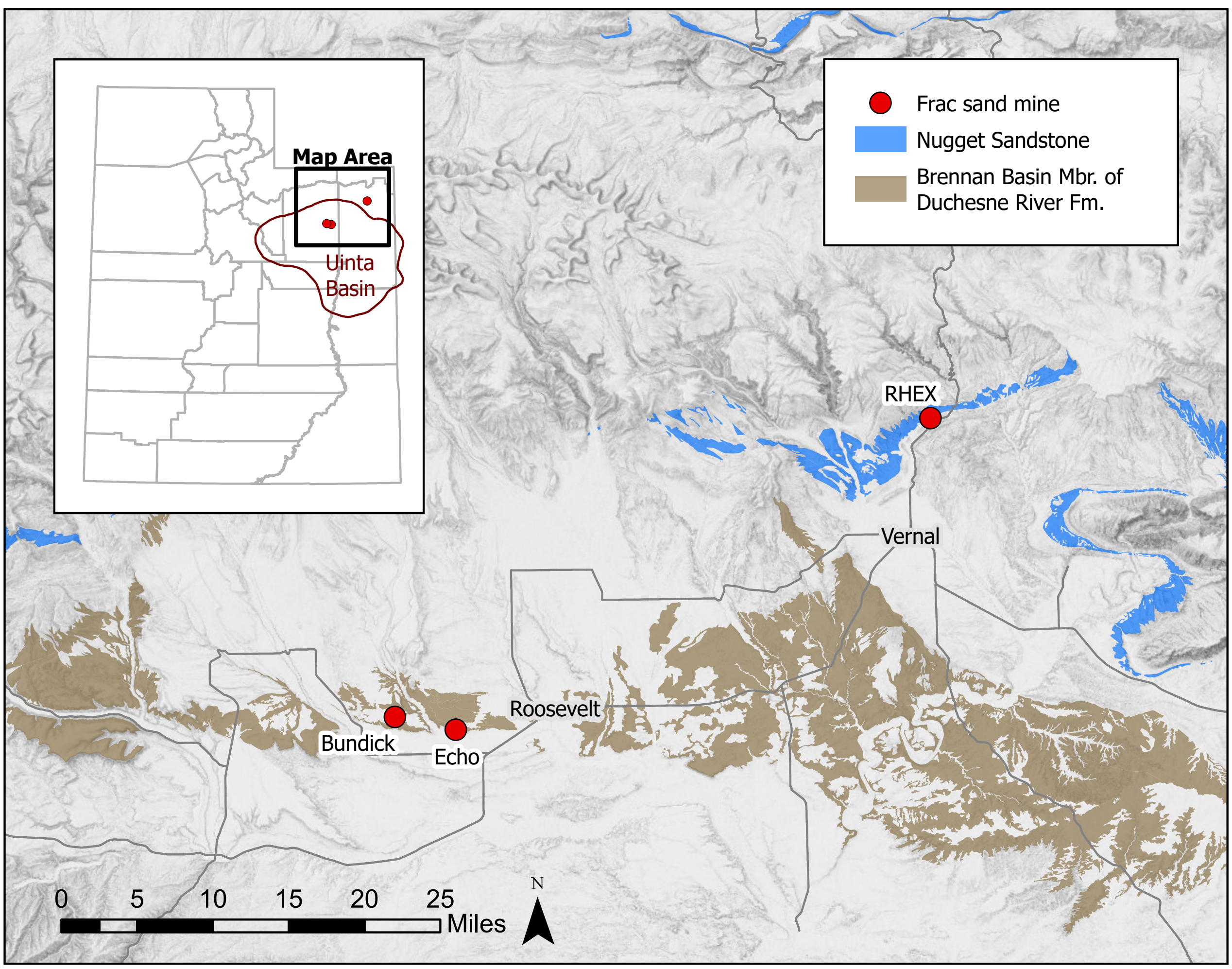

Figure I1. Frac sand mines near the northern Uinta Basin. Geology is from Sprinkel (2006, 2007, 2024). Shaded relief base map provided by Utah Geospatial Resource Center.

More recently, two frac sand mines began producing from sandstone within the Eocene-age Brennan Basin Member of the Duchesne River Formation (Figure I1). The Echo and Bundick mines are operated by Wildcat Sand and SM Energy, respectively, and produce from horizons within the Brennan Basin Member that are sufficiently quartz rich for frac sand. The sandstone being mined is quite friable and disaggregates readily allowing for ease of mining and processing. The Echo mine produces a 40/170 mesh frac sand product and the Bundick mine produces a 30/70 and 50/140 mesh product. Previously, Wildcat Sand also mined unconsolidated eolian sand near their current mine site for frac sand. The extent of suitable sandstone within the Brennan Basin Member is unknown.

The attached report provides details on potential frac sand resources across Utah. However, because suitable sources have been discovered and developed in and near the Uinta Basin, future development of frac sand is likely to remain within or in close proximity to the basin.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

In an effort to evaluate frac sand potential on School and Institutional Trust Lands Administration (SITLA) property, the Utah Geological Survey collected 60 sand and sandstone samples of Permian through Quaternary aged units around Utah. Frac sand is a natural proppant, which is used to keep fractures open after hydraulic fracturing, and it must meet very stringent specifications including high purity, proper grain size, high sphericity and roundness, and high crush resistance. Potential sandstone units must also be sufficiently friable to disaggregate during processing. The Utah Geological Survey evaluated the collected samples for purity, grain size, sphericity and roundness, and also made field observations regarding the friability of sandstone units. Purity was evaluated using semi-quantitative XRF, sieve analysis was used to determine grain size distribution, and sphericity and roundness were visually estimated using the Krumbien/ Sloss chart.

Our results indicate three of the sampled units have the most potential for use as proppant: Permian White Rim/Cedar Mesa Sandstones, White Throne Member of the Temple Cap Formation, and Quaternary eolian sand in southwest Utah. The White Rim/Cedar Mesa Sandstones appear to have potential for a 30/50 sized proppant product given grain size distribution, but roundness was slightly inferior for this unit. The White Throne Member also has high potential, but would likely be more suited to a 40/70 sized proppant product. Eolian sands in southwest Utah also have high potential, and have the distinct advantage of being unconsolidated. Although our semi-quantitative analyses suggest that purity may be an issue for any of the units, better results may be achieved through a true quantitative analysis; processing and washing would likely improve the purity of potential units. Other units also have some potential, such as Jurassic Navajo Sandstone, Jurassic Thousand Pockets Tongue of the Page Sandstone, and Cretaceous capping sandstone of the Wahweap Formation. The Nugget Sandstone near the Uinta Basin may deserve additional investigation due to its proximity to oil and gas fields in the basin. Additional investigation is required to determine if any of the units are fully suitable for use as frac sand, particularly crush resistance testing, which was not a part of this study.

SITLA owns a number of tracts that have exposures of the units with potential. In the San Rafael Swell, SITLA owns a few tracts with exposures of the Permian White Rim/ Cedar Mesa Sandstones, and in Washington and Kane Counties SITLA owns a number of tracts with exposures of the White Throne Member and eolian sands. SITLA also has property covering outcrop of the Nugget Sandstone in Uintah County.

INTRODUCTION

Background and Purpose

Production of frac sand has increased significantly in the U.S. in recent years as hydraulic fracturing (or “fracking”) has become a frequently used technique for oil and gas extraction. Hydraulic fracturing, in combination with horizontal drilling, is commonly used because it allows extraction of oil and gas from geologic formations with low permeability, particularly shale, which has opened up significant domestic resources. Hydraulic fracturing consists of pumping fluids at high pressures into wells to fracture the host rock. One of the components of the fracturing fluid is a “proppant,” which remains in the fractures to keep (or “prop”) them open. The proppant functions as a permeable medium allowing oil and gas to be pumped out of the well. Natural quartz sand can be used as a proppant and is commonly known as frac sand or proppant sand. Frac sand is generally produced from sandstone or unconsolidated sand deposits that meet fairly stringent specifications. Synthetic proppants are also produced, but natural frac sand is cheaper and more commonly used.

The U.S. Geological Survey estimated that 33 million tons (30 million metric tons) of industrial sand was produced in the U.S. in 2011, and 41% of that production was used in the oil and gas industry for frac sand, well-packing sand, and cementing sand (Dolley, 2012). By comparison, the U.S. produced an estimated 31.2 million tons (28.3 million metric tons) of industrial sand in 2003 and only 5% was used for frac sand (Dolley, 2004). Most frac sand currently produced in the U.S. comes from the Midwest and South (O'Driscoll, 2012).

The Utah School and Institutional Trust Lands Administration (SITLA) commissioned the Utah Geological Survey (UGS) to evaluate frac sand potential on SITLA lands. This report presents and summarizes data from sand or sandstone samples collected on or near SITLA lands in an effort to evaluate their suitability for frac sand.

Frac Sand Specifications and Logistics

A number of properties of sand and sandstone deposits are considered when evaluating their suitability for frac sand including (but not limited to) chemistry, particle size, crush resistance, sphericity and roundness, friability, and proximity to transportation, infrastructure, and market. The standardized methods for testing a final proppant product are described in American Petroleum Institute (API) Recommended Practice (RP) 19C and International Organization for Standardization (ISO) standard 13503-2:2006 (API RP 19C recently replaced API RP 56). These methods include procedures for testing particle size, sphericity and roundness, acid solubility, turbidity, density, and crush resistance. These tests act as a partial guide for evaluating a frac sand deposit. We describe, in greater detail, some of the important characteristics of a frac sand deposit below.

Chemistry

Generally, pure quartz sand that is 99% SiO_2 or greater is desired for frac sand (Elliot, 2012; Zdunczyk, 2012). Undesirable minerals or impurities, such as feldspar, often crush before quartz under well pressures, which causes a decrease in permeability. One of the tests described in API RP 19C is acid solubility, which is essentially a test of the purity of the frac sand. The test quantifies how much of a proppant is soluble in acid, which is important because acid is commonly used in the hydraulic fracturing process (Anderson, 2011). However, acid solubility is becoming less important because less acid is being used during the fracking process (Zdunczyk, 2012). Acid solubility can also often be an indication of carbonate content.

Another test described in API RP 19C is the turbidity test, which can also be an indication of purity. The turbidity test measures the amount of silt and clay sized particles in a frac sand sample, and is measured in Formazin Turbidity Units (FTU) (API RP 19C). Turbidity of frac sand can be improved by washing during processing (Anderson, 2011; Zdunczyk, 2012).

Size

Particle size of a frac sand deposit is of key importance. Particle size impacts the permeability of frac sand and affects the strength of the frac sand. Although larger grain size allows for higher permeability, larger grain size also tends to reduce the strength (or crush resistance, see below) of the proppant (Herron, 2006). This inverse relationship between permeability and strength leads to adjusting the optimum grain size for proppants depending on pressures encountered in a well. Proppant sizes are generally defined and marketed as falling between two standard sieve sizes. Table 1 shows the typical proppant size designations that are produced.

The most commonly used frac sand sizes fall between ASTM sieve numbers 20 and 70 (Dustman and others, 2011; Elliot, 2012). However, the 70/140 size is also commonly used as a proppant in gas wells (Zdunczyk, 2012). Overall, the 20/40 fraction is probably the most commonly used size designation (Alberta Geological Survey, 1989; Zdunczyk, 2012).

Table 1. *Typical proppant product size designations.*
From API RP 19C.

ASTM Sieve Size (No.)	Sieve Size (mm)
6/12	3.35/1.70
8/16	2.36/1.18
12/18	1.70/1.00
12/20	1.70/0.850
16/20	1.18/0.850
16/30	1.18/0.600
20/40	0.850/0.425
30/50	0.600/0.300
40/60	0.425/0.250
40/70	0.425/0.212
70/140	0.212/0.106

Crush Resistance

The ability of proppants or frac sand grains to resist being crushed and broken when subjected to high pressures at depth is called “crush resistance.” This is an important characteristic of proppants to maintain permeability in a well. If the down-hole pressures crush, break, and reduce the proppant to finer particles, then permeability in the well is reduced, which reduces the well’s production capability (Zdunczyk, 2012). Crush resistance is determined by subjecting a proppant to a specified known stress level(s) to see how much fines are produced. Crush resistance varies among proppants; the better, unmodified frac sand can withstand pressures without producing excessive fines up to about 6000 pounds per square inch (psi) (Herron, 2006), but guidelines from AP RPI 19C suggest a range of 2000 to 5000 psi. Frac sand can be resin coated to reduce fines production, and can be used in stress ranges from 4000 to 12,000 psi (Herron, 2006). API RPI 19C indicates a maximum stress level for ceramic proppants of about 15,000 psi.

Sphericity and Roundness

To provide good porosity and permeability, frac sand grains should be as spherical and round as possible. At high pressures, angular fragments tend to pack together, which lowers porosity and permeability (Herron, 2006; Zdunczyk, 2012). Sphericity refers to how close a particle is to the shape of a sphere, while roundness is a measure of the relative sharpness of corners on a grain (API RP 19C). The most common tool for visually estimating sphericity and roundness is the Krumbein/Sloss chart (API RP 19C), which ranks both sphericity and roundness on a scale from 0.1 to 0.9. The higher the number, the more spherical or round a particle is. API RP 56 recommends that both sphericity and roundness should be a minimum of 0.6 for frac sand. However, under some low-pressure conditions angular grains are used and can actually improve permeability (Herron, 2006).

Friability

If frac sand is sourced from cemented sandstone, friability is an important characteristic. Cemented sandstone can require additional processing, particularly in the crushing phase, to make it suitable for frac sand. If sandstone is too well-cemented it may be unsuitable because the rock may break across grains, creating angular fragments. A more friable sandstone would also reduce the number of clusters (sample grains that are aggregated together) in a final proppant product.

Proximity to Market and Infrastructure

Proximity to market and infrastructure is an important consideration in locating a frac sand deposit. Cost of transporting frac sand to end users can be significant, and some estimates of transportation costs range from about 33% to 80% of the total cost of the product (Elliot, 2012). Therefore, proximity to end users as well as rail and other major transportation routes is quite important.

Domestic Frac Sand Production and Available Data

Currently, the Midwest accounts for about two-thirds of the frac sand production in the U.S., and the South (primarily Texas) accounts for nearly all of the remaining one-third. A small amount of frac sand is produced in the Northeast and the West (Arizona) (O'Driscoll, 2012). U.S.-produced frac sand is sourced from a number of geologic formations with varying ages. The best frac sand tends to come from geologic units containing sands that have been reworked multiple times to produce clean, well-sorted, and rounded grains. One such unit is the Ordovician St. Peter Sandstone, which is exposed in a number of Midwestern states. The St. Peter Sandstone is a transgressive deposit of reworked beach sediments (Bates, 1960) that has been used extensively for frac sand (Herron, 2006; Elliot, 2012). Another commonly used unit is the Cambrian Hickory Sandstone in Texas. Cook (2010) recently interpreted the Hickory Sandstone as representing a braided delta deposit modified by tides. St. Peter Sandstone has been traditionally called "white sand," and individual sand grains tend to be single quartz crystals, while Hickory Sandstone is called "brown sand" and the quartz grains are generally polycrystalline (Roberts, 2009). The polycrystalline Hickory Sandstone generally has a lower crush resistance than the monocrystalline St. Peter Sandstone (Herron, 2006; Roberts, 2009). Other units exploited in the Midwest include the Cambrian Jordan, Mt. Simon, and Wonewoc Sandstones. Unconsolidated sediments (eolian, fluvial, etc.), in some cases derived from the aforementioned units, are also used as a frac sand source (Herron, 2006; Zdunczyk, 2012).

In the West, frac sand is produced in east-central Arizona from fluvial sands in the Pliocene Bidahochi Formation. Eyde and Eyde (1987) reported that these fluvial sands are derived from Permian sandstones. The Alberta Geological Survey (1989) evaluated and published information on the Cretaceous Peace River Formation as a potential frac sand source. The North Dakota Geological Survey also recently evaluated a number of Tertiary and Quaternary deposits for frac sand potential and published data from their results (Anderson, 2011).

Ceramic proppants are also commonly used as an alternative to natural or resin-coated frac sand. Ceramic proppants are generally produced from sintered bauxite and kaolin. These ceramic proppants typically perform better than natural frac sand because they are produced to desired particle size and roundness, and have higher crush resistance. However, ceramic proppants are significantly more expensive than natural proppants.

Essentially no published data are available regarding the frac sand suitability of sand or sandstone deposits in Utah. Doelling and Davis (1989) briefly mentioned that Navajo Sandstone from Kane County could potentially be a source of frac sand because of its purity.

Methods

This study began with literature searches and geologic map reviews to identify potential silica-rich eolian or dune areas and potential high-silica sandstone units, and where those units are coincident with SITLA property. After identifying these areas, we sampled many of them to evaluate the material. While sampling, we noted geologic characteristics that may be pertinent to frac sand suitability, such as friability and the presence of concretions in the unit. If the sample was taken from an outcrop, we generally took a chip sample along an irregular spacing depending on where on an outcrop we could extract a sample and noted the approximate thickness of the total sample interval. From dune sand sites, our sample consisted of a few shovels full of sand from a single location. The primary tests and evaluations we performed on each sample were sieve analysis, roundness and sphericity evaluation, and chemical analysis. Due to cost constraints we did not have samples tested for crush resistance.

The samples were initially weighed and then split to obtain an adequate amount of sample for sieve analysis. Samples were dry-sieved mechanically on a Gilson SS-8R sieve shaker for 10 minutes. We selected the sieve set based on sizes applicable to marketed frac sand sizes (table 1). Prior to sieving, rock chip samples were gently disaggregated by hand using a hammer and steel roller.

Splits of whole-rock samples and selected size fractions were obtained for chemical analysis. Generally, the largest weight-percent size fraction falling between sieve sizes 20 to 70 was selected for chemical analysis. The sample splits were then pulverized and processed into pressed-powder pellets and analyzed using the UGS's Rigaku miniZSX XRF-WD machine. Processing starts with 4.5 g of pulverized sample being combined with 0.5 g of powdered paraffin. This mixture is then placed in a container and mixed in a mechanical tumbler for approximately 30 minutes. The 5 g sample is poured into an aluminum sample holder (Spex-cap), placed in a pellet die in a hydraulic press, and pressed with 6000 psi of pressure for approximately 2 minutes. The finished pellets were then analyzed using a semi-quantitative analytical application. The semi-quantitative analysis measures the approximate relative elemental components of a sample and normalizes the values to sum at 100%.

Typically, we selected the largest weight-percent size fraction falling between sieve sizes no. 20 and no. 70 for roundness and sphericity evaluation. A minimum of 20 grains from a split of the selected sample were randomly selected to visually estimate roundness and sphericity to the nearest tenth using a Krumbien/Sloss chart. Aggregated grains or smaller grains that had likely been part of an aggregated grain were not used in the evaluation. We report the average sphericity and roundness from the 20 or more grains, rounded to the nearest tenth. We used a 6-40x magnifying binocular microscope for these estimates.

GEOLOGIC UNITS SAMPLED

A number of geologic units were investigated as part of this study, and brief descriptions of these units are presented below from oldest to youngest. Table 2 provides information on the frac sand samples including the name of the geologic unit sampled, and figure 1 shows the locations of the samples.

***Table 2**. Frac sand sample data.*

Sample No.	NAD83, Zone 12 UTM Easting (m)	UTM Northing (m)	Deposit Type	Age	Geologic Unit	Friability	Approximate Thickness of Sampled Interval (ft)	Notes
FS-1	372875	4389767	dune sand	Quaternary	Eolian sand	n/a	n/a	thin dune sand, limited extent
FS-2	387020	4399468	dune sand	Quaternary	Eolian sand	n/a	n/a	thick dune sand, extensive
FS-3	240769	4127767	(ortho?)quartzite	Permian	Queantoweap Sandstone	not friable	n/a	White to tan quartzite, angular fragments
FS-4	284018	4101300	dune sand	Quaternary	Eolian sand	n/a	n/a	orange dune sand is extensive with variable thickness
FS-5	283552	4100618	dune sand	Quaternary	Eolian sand	n/a	n/a	orange dune sand is extensive with variable thickness
FS-6	289201	4107580	sandstone	Jurassic	Navajo Sandstone	very friable	100	mostly tan to orange, cross-bedded sandstone
FS-7	289315	4107727	dune sand	Quaternary	Eolian sand	n/a	n/a	dune sand is extensive with variable thickness
FS-8	350308	4118926	sandstone	Jurassic	Temple Cap Sandstone (White Throne Mbr.)	very friable	30	mostly white, cross-bedded sandstone
FS-9	350309	4118950	sandstone	Jurassic	Temple Cap Sandstone (White Throne Mbr.)	very friable	30	mostly white, cross-bedded sandstone
FS-10	335833	4123316	sandstone	Jurassic	Temple Cap Sandstone (White Throne Mbr.)	very friable	15	white to tan, cross-bedded sandstone
FS-11	335919	4123096	sandstone	Jurassic	Temple Cap Sandstone (White Throne Mbr.)	very friable	4	white, cross-bedded sandstone; sampled from a quarry?
FS-12	354566	4113583	sandstone	Jurassic	Navajo Sandstone	very friable	80	orange to brown, cross-bedded sandstone
FS-13	354589	4113499	sandstone	Jurassic	Navajo Sandstone	very friable	45	orange to brown, cross-bedded sandstone
FS-14	354917	4113988	dune sand	Quaternary	Eolian sand	n/a	n/a	thin dune sand, extent is unknown
FS-15	362415	4108824	sandstone	Jurassic	Navajo Sandstone (Lamb Point Tongue?)	very friable	--	sample taken from existing mine workings
FS-16	432275	4102707	sandstone	Jurassic	Carmel Formation (upper unit)	moderately to very friable	10 to 15	white to gray sandstone, abundant mm-sized concretions in areas
FS-17	437301	4098681	dune sand	Quaternary	Eolian sand	n/a	n/a	dunes extensive in area, variable thickness
FS-18	438024	4104513	sandstone	Jurassic	Page Sandstone, Thousand Pockets Tongue	friable	20	mostly white, cross-bedded sandstone
FS-19	437947	4104450	sandstone	Jurassic	Page Sandstone, Thousand Pockets Tongue	friable	100+	variably colored, cross-bedded sandstone, abundant concretions of variable size in areas
FS-20	441301	4100018	dune sand	Quaternary	Eolian sand	n/a	n/a	thick, extensive dunes
FS-21	441571	4098152	dune sand	Quaternary	Eolian sand	n/a	n/a	thick, extensive dunes
FS-22	441963	4100658	sandstone/siltstone?	Jurassic	Entrada Sandstone	moderately friable	grab sample	white sandstone
FS-23	530199	4299057	sandstone	Permian	White Rim and Cedar Mesa Sandstones (undiff	moderately to very friable	35	white, orange, and brown sandstone; Fe-staining in many areas
FS-24	533375	4295646	sandstone	Permian	White Rim and Cedar Mesa Sandstones (undiff	moderately to very friable	15	white sandstone; Fe-straining; cross-bedded
FS-25	533419	4295649	sandstone	Permian	White Rim and Cedar Mesa Sandstones (undiff	moderately to very friable	40+	tan, white, orange, and red sandstone; variably Fe-stained
FS-26	524134	4291973	sandstone	Permian	White Rim and Cedar Mesa Sandstones (undiff	moderately friable	55	brown and gray to dark gray sandstone; cross-bedded
FS-27	595519	4318717	sandstone/siltstone?	Cretaceous	Sego Sandstone	very friable	10 to 15	white to light gray sandstone; sego not friable in other parts of unit
FS-28	601279	4316556	sandstone	Cretaceous	Castlegate Sandstone (?)	moderately to very friable	15 to 20	light tan to white sandstone; cross-bedded
FS-29	601221	4316595	sandstone	Cretaceous	Castlegate Sandstone (?)	moderately to very friable	55	tan sandstone; small cross-beds
FS-30	649464	4313021	sandstone	Cretaceous	Dakota Sandstone	moderately friable	15 to 20	orange, yellow, and white sandstone; wavy iron staining throughout
FS-31	630245	4247421	sandstone	Jurassic	Wingate Sandstone	moderately to very friable	40	light tan sandstone; cross-bedded
FS-32	640001	4240890	sandstone	Jurassic	Navajo Sandstone	slightly to moderately friabl	--	orange sandstone; cross-bedded; sampled along a mostly horizontal roadcut
FS-33	586277	4279500	sandstone	Jurassic	Navajo Sandstone	mostly very friable	35	light tan sandstone; cross-bedded
FS-34	586381	4279468	dune sand	Quaternary	Eolian sand	n/a	n/a	dune sand in area is variably thick, and seems to be variably pure
FS-35	590638	4282352	sandstone	Jurassic	Navajo Sandstone	moderately to very friable	80	light tan sandstone; cross-bedded
FS-36	595373	4279528	sandstone	Jurassic	Navajo Sandstone	moderately to very friable	60	light tan to white sandstone; cross-bedded; small concretions present towards top
FS-37	595186	4278822	dune sand	Quaternary	Eolian sand	n/a	n/a	tan sand; dunes variably thick in area
FS-38	591622	4276075	dune sand	Quaternary	Eolian sand	n/a	n/a	tan to orange dune sand; dunes not extensive where sampled
FS-39	602148	4276575	sandstone	Jurassic	Navajo Sandstone	moderately to very friable	40	light tan, cross-bedded
FS-40	609651	4301340	sandstone	Jurassic	Navajo Sandstone	not friable to very friable	--	mostly light tan with red, iron-stained zones; very hard in some areas
FS-41	539448	4368851	sandstone/siltstone?	Cretaceous	Ferron Sandstone	not friable	20	tan to gray sandstone and siltstone; large carbonaceous content
FS-42	344258	4190435	sandstone	Cretaceous	Wahweap Formation (Capping sandstone mem	slightly friable	15	pink, impure quartz sandstone
FS-43	338192	4178880	sandstone	Cretaceous	Wahweap Formation (Capping sandstone mem	moderately to very friable	10	light tan to white sandstone; some coarse fragments; from old quarry
FS-44	343710	4183857	sandstone	Cretaceous	Wahweap Formation (Capping sandstone mem	moderately to very friable	50	light tan to white sandstone; cross-bedded
FS-45	342788	4184736	sandstone	Cretaceous	Wahweap Formation (Capping sandstone mem	moderately to very friable	50	mostly white to light tan to orange sandstone; cross-bedded
FS-46	342780	4184757	sandstone	Cretaceous	Wahweap Formation (Capping sandstone mem	moderately to very friable	20	tan sandstone; more competent at base of section
FS-47	316261	4160900	sandstone	Jurassic	Navajo Sandstone	slightly to moderately friabl	40	orange sandstone; very hard in some areas
FS-48	333980	4233998	(ortho?)quartzite	Permian	Queantoweap Sandstone	not friable	n/a	quartzite, angular fragments
FS-49	378744	4292333	sandstone	Jurassic	Navajo Sandstone	not friable to slightly friable	n/a	tan to orange sandstone; sampled float; very hard
FS-50	318078	4581519	(ortho?)quartzite	Permian	Diamond Creek Sandstone	not friable	n/a	quartzite
FS-51	655323	4427481	sandstone	Tertiary	Uinta Formation (Member A)	not friable to very friable	25	Brown fluvial sandstone
FS-52	627784	4467782	sandstone	Cretaceous	Lower Unit of Mesaverde Group	very friable	25	light gray to gray sandstone
FS-53	627823	4467819	dune sand	Quaternary	Eolian sand	n/a	n/a	tan to gray dune sand; limited extent; primarily derived from Lower Unit of Mesaverde Group
FS-54	455361	4431762	sandstone/quartzite	Permian	Diamond Creek Sandstone	not friable	--	very hard, highly-fractured
FS-55	458115	4429428	sandstone	Jurassic	Navajo Sandstone	moderately friable	50+	light-colored sandstone; silicified veinlets common; some Fe concretions
FS-56	629434	4493686	sandstone	Triassic/Jurassic	Nugget Sandstone	mostly very friable	--	white to tan sandstone; cross-bedded
FS-57	646861	4466906	sandstone	Triassic/Jurassic	Nugget Sandstone	moderately to very friable	--	white to orange sandstone; abundant small (mm-sized) concretions
FS-58	646783	4466935	dune/alluvial sand	Quaternary	Eolian/alluvial sand	n/a	n/a	limited extent; primarily derived from Nugget Sandstone
FS-59	640474	4497122	sandstone	Triassic/Jurassic	Nugget Sandstone	mostly very friable	50+	white, yellow, tan sandstone; cross-bedded
FS-60	620315	4485900	sandstone	Triassic/Jurassic	Nugget Sandstone	moderately friable	50+	white to tan sandstone; cross-bedded

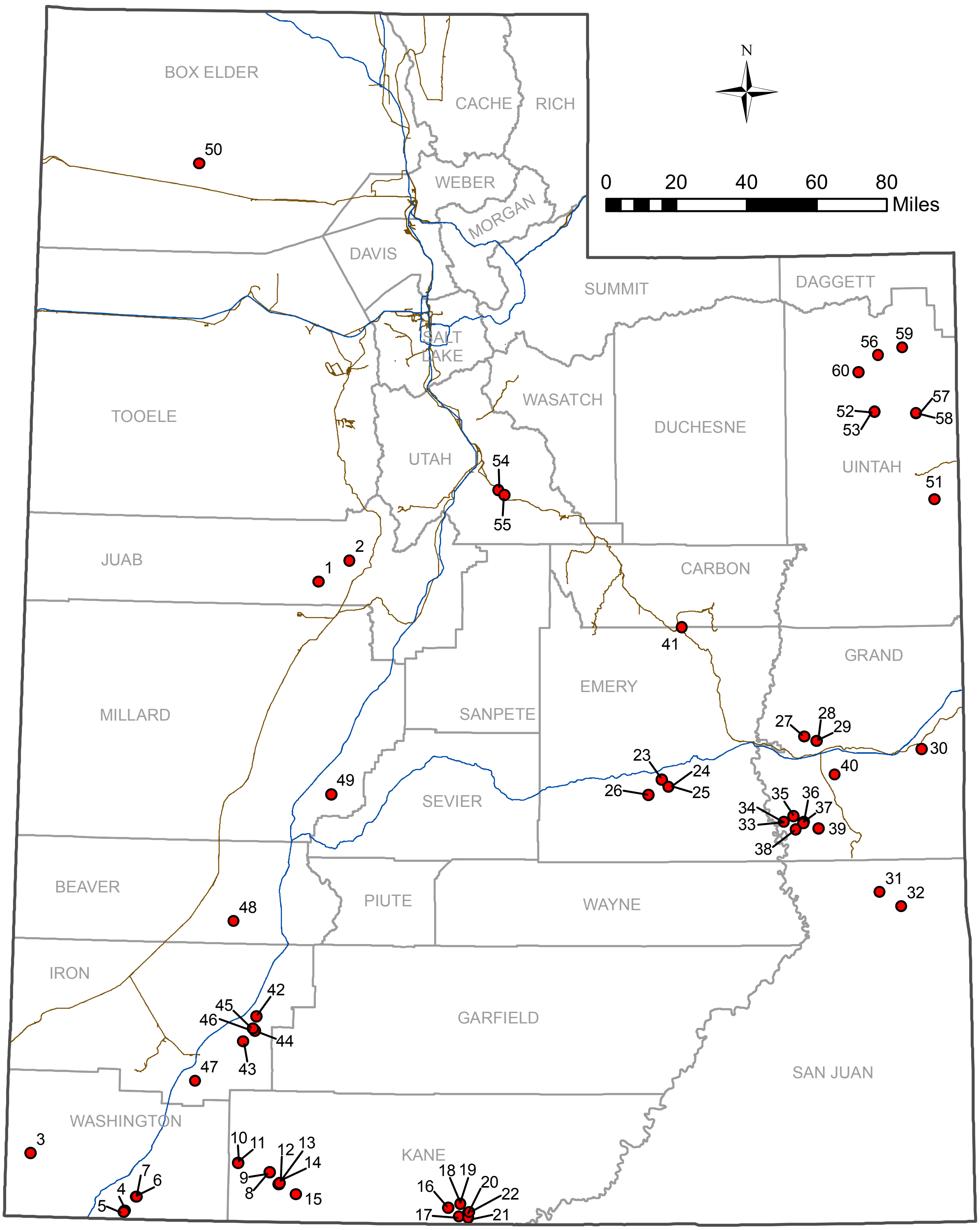

Figure 1. *Frac sand sample locations. Samples are represented as red points, rail is shown as brown lines, and interstate highways are shown as blue lines. Sample numbers correspond to table 2.*

Permian White Rim and Cedar Mesa Sandstones

Doelling (2002b) mapped the White Rim and Cedar Mesa Sandstones as a single unit in the San Rafael Swell area of east-central Utah. He described the unit as eolian, cliff-forming, massive, cross-bedded, light-colored, medium- to coarse-grained sandstone. The unit has prominent brown and red iron-stained zones in the San Rafael Swell, and its thickness ranges from 500 to 950 ft (Doelling, 2002b). We sampled the unit in a few places in the southeastern area of the San Rafael Swell (figure 2).

Permian Diamond Creek Sandstone

We sampled the Diamond Creek Sandstone in the Hogup Mountains and in Spanish Fork Canyon. Doelling (1980) described the Diamond Creek Sandstone of Box Elder County as "tan to yellow, cross-bedded, friable calcareous sandstone and orthoquartzite." In this area, the unit is over 2400 ft thick (Doelling, 1980). We examined and sampled the Diamond Creek Sandstone on the southern tip of the Hogup Mountains and observed mostly orthoquartzite and chert. Friable sandstone may be present as a relatively recessive unit, but we observed none. Constenius and others (2011) described the Diamond Creek Sandstone in the Provo 30' x 60' quadrangle as thick-bedded, fine-grained, friable sandstone with some interbeds of calcareous sandstone. Where we examined the Diamond Creek Sandstone in Spanish Fork Canyon it was massive, very hard, and highly fractured. Constenius and others (2011) reported a thickness range of 450 to 1320 ft for the Diamond Creek Sandstone. Because the unit was very competent and hard in both areas we examined, we did no processing or testing of any samples.

Figure 2*. Exposure of the upper White Rim/Cedar Mesa Sandstones in the San Rafael Swell area in Emery County. Sample FS-23 was collected in this area.*

Permian Queantoweap Sandstone

Biek and others (2010) described the Queantoweap Sandstone in the St. George 30' x 60' quadrangle area as a yellowish-brown to orange, cross-bedded, fine- to medium-grained sandstone. The unit's thickness ranges from about 1400 to 2000 ft in southwestern Utah (Biek and others, 2010). Rowley and others (2005) described the Queantoweap in the Beaver 30' x 60' quadrangle area as tan and pink fine-grained sandstone and quartzite where it reaches a maximum thickness of about 500 ft. We sampled the Queantoweap Sandstone in western Washington County and in Beaver County north of Minersville, and in both areas, the rock is primarily (ortho?) quartzite. Because the unit is extremely hard and not friable where we sampled, we did no processing of the samples.

Triassic-Jurassic Nugget Sandstone

We sampled the Nugget Sandstone in a few exposures in the Uinta Basin, near Vernal. Sprinkel (2006, 2007) described the sandstone as light colored, resistant, and massive with large-scale cross-bedding. The unit is primarily eolian and its thickness ranges from 510 to 1030 ft (Sprinkel, 2006, 2007).

Jurassic Wingate Sandstone

We sampled the eolian Wingate Sandstone south of Moab, and in this area Doelling (2004) described the unit as massive, cross-bedded, fine-grained sandstone. He also noted that the grains are typically subangular and well sorted, and outcrop as generally vertical to rounded cliffs. Thickness is 220 to 420 ft thick in the area (Doelling, 2004). Our sample came from the upper part of the unit.

Jurassic Navajo Sandstone

The outcrop of Navajo Sandstone is extensive in southern Utah and we sampled the unit in Washington, Kane, Grand, San Juan, Iron, Utah, and Millard Counties. The eolian sandstone is variably colored, ranging from red to orange to white, and is fine to medium grained (Doelling, 2002a; Biek and others, 2010). The quartz grains are frosted, well sorted, and well rounded to subangular (Doelling, 2004; Biek and others, 2010). The Navajo exhibits large-scale cross-beds and exhibits iron staining and bleaching in some areas. In the western part of the state, the Navajo is informally divided into three zones: an upper white cliff-forming zone, a middle pink less-resistant zone, and a lower brown zone (Doelling, 2008; Biek and others, 2010). In the western part of the state the Navajo is up to 2300 ft thick, while it is only up to about 740 ft thick in the eastern part of the state (Doelling, 2002a; Biek and others, 2010). We took one sample from what is likely the Lamb Point Tongue of the Navajo Sandstone; this basal tongue is exposed primarily in western Kane County, and is generally a white to light-gray, fine-grained sandstone (Doelling, 2008).

Jurassic Temple Cap Formation – White Throne Member

The White Throne Member of the Temple Cap Formation is a white to light-colored, cross-bedded, quartz sandstone that represents a coastal dune field, and we sampled it in a few areas in western Kane County (figure 3). The sandstone is generally fine to medium grained, well sorted, and the sand grains are frosted. Thickness of the unit in southwestern Utah is up to about 130 ft (Doelling, 2008; Biek and others, 2010).

Figure 3*. Outcrop of the Jurassic White Throne Member of the Temple Cap Formation in western Kane County. Samples FS-8 and FS-9 were collected from this outcrop.*

Jurassic Page Sandstone – Thousand Pockets Tongue

We sampled the (eolian?) Thousand Pockets Tongue of the Page Sandstone in southeastern Kane County. The Thousand Pockets Tongue is yellow, white, and brown, cross-bedded sandstone with some siltstone partings. Its thickness ranges from about 90 to 200 ft (Doelling and Willis, 2006).

Jurassic Carmel Formation

We sampled a thin (approximately 15-ft thick) sandstone unit in southeast Kane County that Doelling and Willis (2006) mapped as part of the upper unit of the Carmel Formation. The unit is laterally continuous, light-gray, fine-grained sandstone with frosted grains and pervasive sub-inch sized concretions.

Jurassic Entrada Sandstone

In southeast Kane County, we collected one sample of Entrada Sandstone. In that area it is primarily light-colored, fine-grained, cliff -forming sandstone. Doelling and Willis (2006) reported that the unit is 330 to 950 ft thick in the area.

Cretaceous Dakota Sandstone

In eastern Grand County, we sampled the upper part of the Dakota Sandstone, which is conglomeratic, cliff- and ledge-forming, yellow, light-gray, and brown sandstone. The full thickness of Dakota Sandstone in the area ranges from 0 to 120 ft (Doelling, 2002a).

Cretaceous Mancos Shale – Ferron Sandstone Member

The Ferron Sandstone consists of marine and fluvial sandstone units with intervening shale units. Witkind (1988) described the sandstone units as "light-brown, thin- and even-bedded, cross bedded, very fine to fine-grained sandstone." We collected one sample of a lower sandstone unit in Emery County near the border of Carbon County where it is a resistant, ledge to cliff-forming unit. The total thickness of the member is 160 ft (Witkind, 1988).

Cretaceous Wahweap Formation – Capping Sandstone Member

We sampled the capping sandstone member of the Wahweap Formation east of Cedar City in Iron County. Biek and others (2012) described the capping sandstone as white to pale orange and very fine- to coarse-grained quartz arenite. The unit is cross-bedded with local iron-staining, and contains conglomeratic beds. Biek and others (2012) noted that the quartz grains are commonly well rounded and frosted, and are likely sourced from Mesozoic eolian units. The unit ranges from about 200 to 277 ft thick (Biek and others, 2012).

Cretaceous Mesaverde Group – Lower Unit

Sprinkel (2007) described the lower unit of the Mesaverde Group as resistant, light-colored, cross-bedded sandstone with minor interbedded shale and coal. We sampled a light gray to gray, friable section of this unit in Uintah County just south of Vernal. The thickness of the lower unit of the Mesaverde Group ranges from 660 to 820 ft (Sprinkel, 2007).

Cretaceous Castlegate Sandstone

In Grand County, Gualitieri (1988) and Doelling (2002a) described the Castlegate Sandstone as light-colored, fine- to medium-grained, cross-bedded, massive, cliff- and bench-forming sandstone with some interbedded mudstone, shale, and coal. The Castlegate ranges in thickness from 10 to 130 ft (Gualitieri, 1988; Doelling, 2002a). We sampled the top part of the formation in central Grand County.

Cretaceous Sego Sandstone

Gualtieri (1988) described the Sego Sandstone of northern Grand County as light-gray to light-brown, fine-grained sandstone that is commonly laminated and medium bedded, and we sampled a light-gray, friable zone of the Sego Sandstone in this area. Most of the sandstone beds we observed in the Sego were quite resistant and ledge-forming. The Sego ranges from about 150 to 210 ft thick (Gualtieri, 1988).

Tertiary (Eocene) Uinta Formation – Member A

Member A of the Uinta Formation is fine- to very fine grained sandstone and siltstone, and is interbedded with minor conglomerate, shale, and tuffaceous sandstone (Sprinkel, 2009). We sampled a ledge-forming section of brown sandstone in Member A near Bonanza, Utah. Member A ranges from about 200 to 460 ft thick (Sprinkel, 2009).

Quaternary Eolian Deposits

Recent eolian sand deposits are scattered throughout various areas of the state, and we sampled a number of these deposits. We sampled a number of deposits in southern Utah in both the west and east (figures 4 and 5). We also sampled the dunes of Little Sahara in Juab County and dunes in Uintah County. As expected, the eolian deposits were variable in thickness and extent from area to area. The deposits ranged from being silica-rich to having a strong carbonate component.

Figure 4. *Eolian sand dunes in southern Washington County. Samples FS-4 and FS-5 were collected in this area.*

Figure 5. *Eolian sand dunes in southeast Kane County. Samples FS-20 and FS-21 were collected in this area.*

TEST RESULTS

Chemistry

Semi-quantitative chemical analyses of whole rock and selected size fractions of frac sand samples are presented in table 3. Based on our semi-quantitative analyses, none of the samples have SiO_2 contents of 99% or purer. However, many samples indicate high SiO_2 content—the highest SiO_2 result was 98.3% from the no. 50 fraction of a dune sand (FS-7) in Washington County. Samples from a few units (whole rock or selected size fractions) indicated 97% or higher SiO_2; those units include the White Rim/Cedar Mesa Sandstones, White Throne Member of the Temple Cap Formation, the capping sandstone of the Wahweap Formation, and eolian sand. Samples from the Nugget Sandstone, Navajo Sandstone, Thousand Pockets Tongue of the Page Sandstone, Mesaverde Group, and Castlegate Sandstone showed 95% or higher SiO_2 content. With few exceptions, the size fractions we selected for chemical analyses had a higher SiO_2 content than the whole-rock analyses—indicating that most of the impurities are likely to be in the fines (material passing the no. 140 sieve). This observation suggests that processing and washing may improve the general chemistry of a particular size fraction by removing fine material that may adhere to larger particles.

Although our results do not show 99% SiO_2 purity, true quantitative analyses may indicate higher SiO_2 than our semi-quantitative analyses. For each analytical run, we ran a known standard of relatively pure sand (97.8% SiO_2), and our semi-quantitative analyses of that sample returned consistently lower SiO_2 contents (typically 0.8 to 1.1%) than the actual certified value. The semi-quantitative results also consistently overestimated impurities such as Al_2O_3, Fe_2O_3, CaO, and K_2O in the standard.

Sieve Analysis

Sieve analyses reported in weight percent of material retained for each size fraction are presented in table 4 and raw sieve data are in appendix A. Overall, the two sieve sizes that retained the most material in our sieve configuration were no. 50 and no. 140. A number of geologic units contained a significant component of material (over 15%) between sieve size no. 40 and no. 50, including the White Rim/Cedar Mesa Sandstones, Navajo Sandstone, White Throne Member of the Temple Cap Formation, Thousand Pockets Tongue of the Page Sandstone, Dakota Sandstone, capping sandstone member of the Wahweap Formation, Mesaverde Group, and eolian sand. Only a few samples contained a substantial component of material (over 10%) between no. 30 and no. 40: three samples from the White Rim/Cedar Mesa Sandstones and one sample each from the Navajo Sandstone, White Throne Member, and eolian sand (figure 6). A minimal amount of material was retained on the no. 30 sieve size for any of the samples. For samples that contained high percentages of material retained on the no. 50 and no. 140 sieves, usually a significant, although lesser, amount of material was retained on the no. 60 and no. 70 sieve sizes (commonly over 10% for each size). Our results indicate geographic variability within individual rock units. Most notably, the Navajo Sandstone seems to be finer grained in the eastern part of the state than the western part, as a relatively insignificant percentage of material was retained above the no. 70 sieve in most of the Navajo samples from the eastern part of the state.

Our sieve test results suggest that a 20/40 frac sand product (or any other proppant product with a larger grain size) is not viable in any of the sampled areas due to the lack of

Table 3 *. XRF semi-quantitative analytical results for frac sand samples.*

Sample No.	Geologic Unit	Weight percent															
		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	SrO	ZrO_2	Total
FS-1 No. 140	Eolian sand	0.44	2.38	6.82	61.3	0.205	0.064	0.065	3.86	19.60	0.61	--	0.09	4.26	0.13	--	99.83
FS-2 No. 140	Eolian sand	0.57	2.11	6.51	62.3	0.203	0.045	0.062	3.32	19.30	0.57	--	0.08	4.68	0.14	--	99.89
FS-4	Eolian sand	0.05	0.22	1.66	95.1	0.022	0.010	0.007	1.19	0.24	--	0.15	--	1.27	--	0.025	99.94
FS-4 No. 50	Eolian sand	--	0.12	0.62	97.5	0.017	0.013	0.006	0.36	0.19	--	0.13	--	1.02	--	--	99.97
FS-5	Eolian sand	0.08	0.28	2.38	93.3	0.029	0.013	0.004	2.16	0.18	0.13	0.11	--	1.24	--	0.023	99.93
FS-5 No. 50	Eolian sand	--	0.07	0.62	97.4	--	0.011	0.004	0.44	0.09	--	0.16	--	1.17	--	--	99.96
FS-6	Navajo SS	0.07	0.06	3.25	92.0	0.058	0.014	0.101	2.75	0.17	--	0.16	--	1.26	--	0.028	99.92
FS-6 No. 50	Navajo SS	0.07	0.05	1.27	96.3	0.026	0.015	0.055	0.91	0.07	--	0.14	--	1.00	--	--	99.90
FS-7	Eolian sand	--	0.04	0.92	96.9	0.019	--	--	0.93	0.05	--	0.16	--	0.88	--	--	99.90
FS-7 No. 50	Eolian sand	--	0.05	0.36	98.3	0.016	--	--	0.25	0.02	--	0.11	--	0.86	--	--	99.96
FS-8	White Throne	--	--	1.30	96.5	0.042	0.011	0.004	1.05	0.05	--	0.17	--	0.82	--	--	99.95
FS-8 No. 50	White Throne	--	0.04	0.51	98.0	0.024	--	0.004	0.31	0.03	--	0.15	--	0.90	--	--	99.97
FS-9	White Throne	0.18	0.05	1.29	96.4	0.023	--	--	1.17	0.04	--	0.11	--	0.65	--	--	99.91
FS-9 No. 50	White Throne	--	0.09	0.60	97.8	0.017	0.014	0.015	0.44	0.02	--	0.13	--	0.85	--	--	99.97
FS-10	White Throne	--	--	1.12	96.7	0.018	0.012	--	1.05	0.03	--	0.13	--	0.86	--	--	99.92
FS-10 No. 50	White Throne	--	--	0.48	98.2	--	0.010	0.015	0.37	0.03	--	0.11	--	0.75	--	--	99.96
FS-11	White Throne	0.05	0.07	2.03	95.2	0.037	0.063	0.014	1.63	0.06	--	0.14	--	0.67	--	--	99.96
FS-11 No. 50	White Throne	--	--	0.84	97.5	0.020	0.036	0.006	0.65	0.02	--	0.13	--	0.77	--	--	99.98
FS-12	Navajo SS	0.05	0.09	3.06	92.0	0.039	--	--	3.18	0.06	0.18	0.14	--	1.15	--	--	99.95
FS-12 No. 70	Navajo SS	0.24	0.04	1.53	95.2	--	0.011	0.007	1.51	0.03	--	0.18	--	1.19	--	--	99.95
FS-13	Navajo SS	0.04	0.09	2.68	93.1	0.034	--	0.007	2.54	0.05	0.14	0.14	--	1.09	--	0.028	99.94
FS-13 No. 60	Navajo SS	0.04	0.04	1.19	96.5	--	0.012	0.009	0.86	0.04	--	0.17	--	1.11	--	--	99.97
FS-14	Eolian sand	0.06	0.11	1.89	94.9	0.034	0.011	--	1.54	0.06	--	0.11	--	1.21	--	--	99.92
FS-14 No. 50	Eolian sand	--	--	0.50	97.9	0.015	0.010	0.005	0.30	0.03	--	0.14	--	1.03	--	--	99.92
FS-15	Navajo SS	0.04	0.07	2.12	93.9	0.048	0.013	0.004	2.76	0.07	--	0.14	--	0.78	--	--	99.94
FS-15 No. 50	Navajo SS	--	--	0.96	96.6	0.025	0.011	--	1.27	0.04	--	0.12	--	0.87	--	--	99.90
FS-16	Carmel Fm.	0.14	1.73	3.96	82.9	0.082	0.169	0.012	3.40	4.37	0.26	0.13	0.06	2.29	0.02	--	99.53
FS-16 No. 50	Carmel Fm.	0.08	1.35	2.88	88.0	0.051	0.173	0.005	2.19	3.19	0.18	0.11	0.04	1.66	0.03	--	99.93
FS-17	Eolian sand	--	0.08	1.49	95.6	0.020	0.015	--	1.40	0.08	--	0.14	--	1.14	--	--	99.97
FS-17 No. 50	Eolian sand	--	0.04	0.70	97.7	--	0.009	--	0.49	0.05	--	0.11	--	0.88	--	--	99.98
FS-18	Thousand P.	--	0.14	2.33	94.2	0.026	--	0.005	2.15	0.10	--	0.17	--	0.80	--	--	99.92
FS-18 No. 50	Thousand P.	--	0.05	1.08	96.8	--	--	0.004	0.86	0.05	--	0.15	--	0.97	--	--	99.95
FS-19	Thousand P.	0.04	0.36	2.58	93.2	0.020	--	0.008	2.01	0.64	--	0.10	--	0.98	--	--	99.94
FS-19 No. 50	Thousand P.	--	0.23	1.39	95.7	0.020	--	--	1.02	0.40	--	0.15	--	1.04	--	--	99.94
FS-20	Eolian sand	--	0.13	1.63	95.2	0.026	--	--	1.59	0.05	--	0.14	--	1.12	--	--	99.88
FS-20 No. 50	Eolian sand	0.16	0.05	0.64	97.6	0.013	0.012	0.009	0.43	0.03	--	0.12	--	0.89	--	--	99.96
FS-21	Eolian sand	--	0.13	2.38	93.3	0.015	--	0.005	2.47	0.06	0.15	0.12	--	1.21	--	0.052	99.89
FS-21 No. 60	Eolian sand	--	0.09	1.15	96.4	0.024	0.013	--	1.00	0.04	--	0.12	--	1.12	--	--	99.96
FS-22	Entrada SS	0.30	0.57	6.79	85.1	0.022	0.011	0.009	4.53	0.40	0.29	0.09	--	1.74	--	0.034	99.88
FS-22 No. 50	Entrada SS	0.38	0.66	7.23	83.9	--	0.015	0.005	5.01	0.39	0.24	0.11	--	2.00	0.02	--	99.96
FS-23	White Rim/CM	--	0.07	1.26	96.1	0.102	0.064	0.012	0.68	0.34	--	0.14	--	1.05	0.07	--	99.90
FS-23 No. 50	White Rim/CM	--	0.09	0.79	97.1	0.079	0.054	0.007	0.36	0.22	--	0.14	--	1.02	0.06	--	99.91
FS-24	White Rim/CM	--	0.04	0.70	96.9	0.026	0.182	0.015	0.55	0.45	--	0.09	--	0.94	--	--	99.89
FS-24 No. 50	White Rim/CM	--	0.10	0.35	97.9	0.019	0.064	0.013	0.17	0.20	--	0.15	--	0.96	--	--	99.92
FS-25	White Rim/CM	--	0.04	0.49	97.1	0.086	0.156	0.009	0.30	0.21	--	0.14	--	1.37	0.06	--	99.96

(continued)

__Table 3__ . XRF semi-quantitative analytical results for frac sand samples.

Sample No.	Geologic Unit	Weight percent Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	SrO	ZrO_2	Total
FS-25 No. 50	White Rim/CM	--	0.05	0.29	97.8	0.074	0.081	0.004	0.12	0.10	--	0.15	--	1.27	0.05	--	99.98
FS-26	White Rim/CM	--	0.05	1.19	95.7	0.090	0.442	0.007	0.78	0.16	--	0.12	--	1.37	0.05	--	99.96
FS-26 No. 50	White Rim/CM	--	--	0.67	97.2	0.027	0.218	0.007	0.39	0.11	--	0.16	--	1.15	0.03	--	99.96
FS-27	Sego SS	0.55	0.48	7.23	80.4	0.107	2.440	0.011	3.17	3.25	0.32	0.08	0.05	1.87	--	--	99.96
FS-27 No. 70	Sego SS	0.38	0.29	4.23	86.5	0.066	1.890	0.014	1.89	2.37	0.17	0.16	--	1.94	--	0.028	99.94
FS-28	Castlegate SS	--	1.64	1.32	90.8	0.093	0.044	0.012	0.61	3.78	--	0.14	--	1.41	--	0.045	99.89
FS-28 No. 50	Castlegate SS	--	3.44	1.03	83.0	0.098	0.074	0.008	0.44	9.25	--	0.14	0.05	2.36	--	0.040	99.92
FS-29	Castlegate SS	--	0.65	1.00	94.2	0.042	0.042	0.009	0.24	2.09	0.11	0.14	--	1.40	--	0.038	99.95
FS-29 No. 70	Castlegate SS	--	0.48	0.81	95.3	0.045	0.033	0.006	0.18	1.56	--	0.15	--	1.34	--	--	99.91
FS-30	Dakota SS	1.14	0.28	5.11	89.9	0.069	0.065	0.008	0.75	0.22	0.44	0.11	--	1.90	--	--	99.99
FS-30 No. 50	Dakota SS	0.98	0.13	3.79	92.3	0.059	0.041	0.007	0.56	0.11	0.23	0.12	--	1.59	--	--	99.91
FS-31	Wingate SS	0.10	1.87	6.96	76.7	0.112	0.055	0.020	6.78	4.96	0.51	0.09	--	1.74	0.06	--	99.96
FS-31 No. 50	Wingate SS	--	2.33	6.03	73.9	0.095	0.038	0.029	5.89	8.54	0.44	0.14	0.12	2.31	0.06	--	99.93
FS-32	Navajo SS	0.18	0.28	5.28	86.5	0.035	0.020	0.087	5.81	0.20	0.24	0.09	--	1.18	0.03	--	99.94
FS-32 No. 140	Navajo SS	0.16	0.20	4.35	88.8	0.025	0.019	0.064	4.85	0.10	0.15	0.12	--	1.12	0.03	--	99.98
FS-33	Navajo SS	0.11	0.05	4.45	87.6	0.039	0.014	0.019	4.88	1.40	0.19	0.09	--	1.10	--	0.032	99.97
FS-33 No. 140	Navajo SS	0.19	0.09	3.79	90.1	0.023	0.008	0.016	3.85	0.70	--	0.12	--	1.05	--	--	99.94
FS-34	Eolian sand	0.06	0.27	3.33	90.9	0.027	0.014	0.009	3.35	0.58	--	0.12	--	1.25	--	0.029	99.93
FS-34 No. 140	Eolian sand	0.09	0.31	3.32	91.0	0.021	0.014	0.011	3.34	0.47	0.15	0.10	--	1.15	--	--	99.98
FS-35	Navajo SS	0.06	0.19	4.94	86.5	0.055	0.015	0.012	5.00	1.59	0.28	0.09	--	1.15	--	0.046	99.92
FS-35 No. 70	Navajo SS	0.05	0.12	2.93	91.6	0.027	--	0.013	2.88	0.84	0.18	0.13	--	1.12	--	--	99.88
FS-36	Navajo SS	--	0.16	4.33	87.9	0.045	0.021	0.013	4.16	1.95	0.17	0.10	--	1.03	--	0.035	99.91
FS-36 No. 60	Navajo SS	0.04	0.09	2.20	93.4	0.024	0.014	0.012	2.01	1.15	--	0.08	--	0.88	--	--	99.90
FS-37	Eolian sand	0.13	0.45	4.48	86.2	0.068	0.013	0.030	4.20	2.62	--	0.10	0.05	1.53	--	0.068	99.94
FS-37 No. 140	Eolian sand	0.08	0.35	4.39	88.2	0.037	0.015	0.012	3.69	1.50	0.18	0.13	--	1.32	--	--	99.90
FS-38	Eolian sand	0.09	0.38	3.79	88.9	0.053	0.016	0.006	3.49	1.36	0.20	0.11	--	1.52	--	0.042	99.96
FS-38 No. 70	Eolian sand	0.05	0.35	2.54	92.3	0.041	--	0.006	1.96	1.16	0.12	0.13	--	1.26	--	--	99.92
FS-39	Navajo SS	0.10	0.19	4.28	89.1	0.039	0.010	0.005	4.60	0.40	0.22	0.11	--	0.84	--	0.031	99.92
FS-39 No. 140	Navajo SS	0.05	0.15	3.71	90.9	0.033	0.011	0.007	3.70	0.20	0.16	0.11	--	0.93	--	--	99.96
FS-40	Navajo SS	0.06	0.25	4.85	81.2	0.053	0.029	0.008	4.24	7.60	0.24	0.08	--	1.26	--	0.041	99.91
FS-40 No. 140	Navajo SS	0.20	0.18	3.90	86.2	0.032	0.036	0.005	3.45	4.54	0.15	0.11	--	1.08	--	--	99.88
FS-41	Ferron SS	0.11	1.25	6.19	83.2	0.366	0.200	0.044	2.46	2.80	0.57	0.11	--	2.58	0.04	--	99.92
FS-43	Wahweap Fm.	--	--	1.51	97.5	0.022	0.020	0.007	0.11	0.03	--	0.12	--	0.61	--	0.024	99.96
FS-43 No. 50	Wahweap Fm.	--	--	0.65	98.3	0.016	0.024	0.004	0.07	0.02	--	0.15	--	0.70	--	--	99.92
FS-44	Wahweap Fm.	--	--	1.03	97.6	--	0.011	0.005	0.09	0.08	0.10	0.12	--	0.91	--	--	99.94
FS-44 No. 60	Wahweap Fm.	--	0.08	0.81	98.0	0.015	0.024	0.005	0.06	0.06	--	0.11	--	0.73	--	--	99.90
FS-45	Wahweap Fm.	0.09	0.07	1.89	96.1	--	0.078	0.125	0.16	0.15	0.16	0.10	--	1.00	--	0.044	99.96
FS-45 No. 60	Wahweap Fm.	0.04	0.05	0.95	97.3	0.019	0.054	0.061	0.09	0.09	--	0.17	--	1.08	--	--	99.91
FS-45 No. 70	Wahweap Fm.	0.04	0.04	1.10	97.4	0.015	0.048	0.053	0.11	0.06	--	0.14	--	0.95	--	--	99.96
FS-46	Wahweap Fm.	0.09	0.14	3.27	94.1	0.014	0.160	0.172	0.20	0.21	0.24	0.16	--	1.14	--	0.053	99.95
FS-46 No. 50	Wahweap Fm.	0.07	0.11	2.58	95.2	--	0.189	0.141	0.15	0.25	--	0.14	--	1.15	--	--	99.99
FS-47	Navajo SS	0.05	0.14	4.86	92.5	0.124	0.035	0.046	0.41	0.26	0.21	0.07	--	1.22	--	--	99.91
FS-47 No. 70	Navajo SS	--	0.08	2.20	96.0	0.068	0.014	0.024	0.20	0.13	--	0.14	--	1.06	--	--	99.90
FS-51	Uinta Fm.	3.23	2.37	10.00	57.6	0.250	0.522	0.009	4.79	10.30	0.89	0.11	0.10	7.96	0.12	--	98.26
FS-51 No. 140	Uinta Fm.	3.17	2.29	9.99	60.5	0.238	0.432	0.010	4.87	8.27	0.72	0.07	0.14	7.80	0.10	--	98.60

(continued)

Table 3 *. XRF semi-quantitative analytical results for frac sand samples.*

	Geologic	Weight percent															
Sample No.	**Unit**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Cr_2O_3**	**MnO**	**Fe_2O_3**	**SrO**	**ZrO_2**	**Total**
FS-52	Mesaverde	--	0.16	2.83	95.0	0.060	0.048	0.014	0.61	0.18	0.25	0.09	--	0.69	--	0.026	99.96
FS-52 No. 50	Mesaverde	--	0.14	2.29	95.6	0.081	0.061	0.015	0.48	0.17	0.16	0.12	--	0.78	0.02	--	99.91
FS-53	Eolian sand	0.04	0.12	1.98	95.7	0.062	0.038	0.013	0.59	0.19	0.19	0.09	--	0.89	--	0.032	99.93
FS-53 No. 60	Eolian sand	--	0.12	1.87	96.3	0.077	0.027	0.007	0.52	0.14	--	0.09	--	0.83	--	--	99.97
FS-55	Navajo SS	0.06	0.22	5.18	88.6	0.026	0.014	0.004	4.15	0.08	0.28	0.12	--	1.13	--	0.042	99.90
FS-55 No. 140	Navajo SS	0.05	0.15	3.45	92.1	0.029	--	0.004	2.83	0.06	0.13	0.10	--	1.03	--	--	99.93
FS-56	Nugget SS	0.06	0.17	3.03	91.8	0.045	0.009	0.005	2.85	0.83	--	0.15	--	1.03	--	--	99.97
FS-56 No. 60	Nugget SS	0.04	0.08	1.31	96.0	--	0.011	0.006	1.09	0.44	--	0.13	--	0.79	--	--	99.89
FS-57	Nugget SS	--	0.14	2.82	88.1	0.039	0.020	0.014	2.54	2.75	0.13	0.12	--	3.21	--	--	99.89
FS-57 No. 60	Nugget SS	--	0.06	1.38	94.7	0.020	0.012	0.013	1.07	1.30	--	0.12	--	1.23	--	--	99.90
FS-58	Eol/allv sand	0.09	0.18	2.96	91.8	0.043	0.021	0.006	2.93	0.63	0.17	0.11	--	0.98	--	0.028	99.95
FS-58 No. 60	Eol/allv sand	0.08	0.12	1.90	94.1	0.036	0.018	0.005	1.72	0.78	--	0.15	--	1.02	--	--	99.93
FS-59	Nugget SS	0.07	0.21	3.85	91.1	0.054	--	0.012	3.49	0.19	--	0.10	--	0.90	--	--	99.97
FS-59 No. 70	Nugget SS	--	0.11	2.22	94.4	0.027	--	0.006	2.18	0.11	--	0.13	--	0.78	--	--	99.96
FS-60	Nugget SS	0.07	0.19	4.54	89.5	0.054	0.019	0.009	3.88	0.12	0.23	0.08	--	1.23	--	0.025	99.95
FS-60 No. 60	Nugget SS	--	0.10	2.02	94.9	0.034	0.013	0.007	1.58	0.05	--	0.12	--	1.07	--	--	99.90

Notes:

For each analytical run, we ran a known standard of relatively pure sand (97.8 SiO_2), and our semi-quantitative analyses consistently returned lower SiO_2 contents (typically 0.8 to 1.1%) than the actual certified value. The semi-quantitative results also consistently overestimated impurities such as Al_2O_3, Fe_2O_3, CaO, and K_2O in the standard.

Table 4 *. Sieve results from frac sand samples.*

		Weight Percent of Material Retained on Sieve No.											
Sample No.	**Geologic Unit**	**8**	**12**	**16**	**18**	**20**	**30**	**40**	**50**	**60**	**70**	**140**	**Pan**
FS-1	Eolian sand	0	0	0	0	0	0	0	0.1	0.3	0.9	84.3	14.5
FS-2	Eolian sand	0	0	0	0	0	0	0	0	0	0.3	89.4	10.3
FS-4	Eolian sand	0	0	0	0	0	0.9	14.1	23.1	9.4	8.2	39.3	5.0
FS-5	Eolian sand	0	0	0	0	0	0	1.3	14.0	10.5	9.4	54.6	10.2
FS-6	Navajo Sandstone	0	0	0	0	0	~~1.5~~	*3.1*	17.3	10.0	8.4	51.0	8.9
FS-7	Eolian sand	0	0	0	0	0	0	1.7	34.9	15.6	11.2	33.8	2.7
FS-8	White Throne Mbr.	0	0	0	0	0	0	11.4	45.9	15.2	7.7	15.9	3.9
FS-9	White Throne Mbr.	0	0	0	0	0	0	2.7	42.3	17.5	13.0	22.6	1.8
FS-10	White Throne Mbr.	0	0	0	0	0	0	4.5	31.0	23.8	16.7	22.9	1.1
FS-11	White Throne Mbr.	0	0	0	0	0	~~1.1~~	8.7	42.5	14.7	12.2	18.2	2.5
FS-12	Navajo Sandstone	0	0	0	0	0	0	~~0.4~~	*3.2*	8.5	11.4	65.2	11.4
FS-13	Navajo Sandstone	0	0	0	0	0	0	*0.9*	17.2	18.1	11.3	39.7	12.7
FS-14	Eolian sand	0	0	0	0	0	0	1.9	23.0	15.6	11.9	40.6	7.0
FS-15	Navajo Sandstone	0	0	0	0	0	0.8	10.6	16.7	9.8	8.0	46.0	8.1
FS-16	Carmel Fm.	0	0	~~9.9~~	~~4.7~~	~~3.7~~	~~6.5~~	~~5.4~~	11.4	8.9	7.8	35.0	6.9
FS-17	Eolian sand	0	0	0	0	0	0	3.1	40.6	17.1	10.2	25.7	3.5
FS-18	Thousand Pockets	0	0	0	0	0	0	*6.8*	21.8	12.5	11.3	44.7	3.0
FS-19	Thousand Pockets	0	0	0	0	0	~~2.0~~	*2.1*	24.4	14.8	14.6	35.4	6.7
FS-20	Eolian sand	0	0	0	0	0	0	3.3	32.2	16.3	10.0	33.5	4.8
FS-21	Eolian sand	0	0	0	0	0	0	0	4.0	16.0	15.4	58.1	6.4
FS-22	Entrada Sandstone	0	0	0	0	0	0	~~4.2~~	~~5.1~~	~~3.0~~	*3.9*	67.8	16.1
FS-23	White Rim/Cedar Mesa	0	0	0	0	0	*1.8*	19.9	29.3	15.5	10.9	20.9	1.6
FS-24	White Rim/Cedar Mesa	0	0	0	0	0	0.3	17.2	29.2	13.6	10.6	25.7	3.3
FS-25	White Rim/Cedar Mesa	0	0	0	0	0	~~1.0~~	16.9	33.5	15.0	10.6	21.2	1.8
FS-26	White Rim/Cedar Mesa	0	0	0	0	0	~~2.3~~	*5.9*	19.2	16.1	14.1	38.3	4.1
FS-27	Sego Sandstone	0	0	0	0	0	0	~~7.8~~	~~8.2~~	~~7.0~~	*9.6*	57.6	9.7
FS-28	Castlegate Sandstone	0	0	0	0	0	~~1.5~~	~~2.7~~	~~4.0~~	~~2.8~~	*3.5*	71.9	13.4
FS-29	Castlegate Sandstone	0	0	0	0	0	0	~~2.6~~	~~5.5~~	*7.9*	11.5	69.0	3.5
FS-30	Dakota Sandstone	0	0	0	0	0	~~4.0~~	~~8.9~~	35.9	23.8	11.3	13.3	2.8
FS-31	Wingate Sandstone	0	0	0	0	0	~~5.2~~	~~3.7~~	~~5.0~~	~~3.3~~	~~3.2~~	50.0	29.6
FS-32	Navajo Sandstone	0	0	0	0	0	~~2.1~~	~~1.3~~	~~1.8~~	~~2.1~~	*3.2*	68.7	20.7
FS-33	Navajo Sandstone	0	0	0	0	0	0	~~2.3~~	~~3.2~~	~~2.7~~	~~3.6~~	78.6	9.6
FS-34	Eolian sand	0	0	0	0	0	0	0	*0.2*	*1.0*	3.2	85.7	9.9
FS-35	Navajo Sandstone	0	0	0	0	0	0	~~3.3~~	~~3.7~~	*4.2*	*5.9*	65.0	17.9
FS-36	Navajo Sandstone	0	0	0	0	0	0	~~2.5~~	*8.4*	12.4	11.1	47.3	18.4
FS-37	Eolian sand	0	0	0	0	0	0	0	*1.3*	3.3	6.2	70.1	19.1
FS-38	Eolian sand	0	0	0	0	0	0	0	*0.9*	4.4	9.0	69.8	15.8

(continued)

Table 4 *. Sieve results from frac sand samples.*

Sample No.	Geologic Unit	Weight Percent of Material Retained on Sieve No.											
		8	12	16	18	20	30	40	50	60	70	140	Pan
FS-39	Navajo Sandstone	0	0	0	0	0	0	~~1.2~~	~~1.6~~	*2.1*	3.6	78.6	12.9
FS-40	Navajo Sandstone	0	0	0	0	0	0	~~2.8~~	~~5.0~~	~~4.5~~	~~4.1~~	66.2	17.4
FS-41	Ferron Sandstone	0	0	0	0	0	0	~~9.3~~	~~5.9~~	~~6.6~~	~~3.3~~	~~16.2~~	58.7
FS-43	Wahweap Fm.	0	0	0	0	0	~~0.7~~	*4.2*	25.5	20.3	13.6	30.6	5.1
FS-44	Wahweap Fm.	0	0	0	0	0	~~0.4~~	*1.1*	13.9	16.0	15.9	49.0	3.8
FS-45	Wahweap Fm.	0	0	0	0	0	~~1.0~~	*1.5*	8.6	10.8	12.4	54.5	11.2
FS-46	Wahweap Fm.	0	0	0	0	0	~~2.0~~	~~2.8~~	9.5	9.4	9.5	50.2	16.7
FS-47	Navajo Sandstone	0	0	0	0	0	0	~~2.4~~	~~5.4~~	*9.0*	11.0	59.3	12.9
FS-51	Uinta Fm.	0	0	0	0	0	~~7.7~~	~~14.0~~	*18.5*	*13.1*	*9.5*	25.8	11.4
FS-52	Mesaverde Group	0	0	0	0	0	~~1.4~~	6.1	28.7	16.9	8.8	27.3	10.8
FS-53	Eolian sand	0	0	0	0	0	0.1	1.1	13.5	19.4	15.7	45.3	5.0
FS-55	Navajo Sandstone	0	0	0	0	0	0	*3.5*	~~2.4~~	*1.9*	*2.8*	63.3	26.0
FS-56	Nugget Sandstone	0	0	0	0	0	0	*0.4*	*11.3*	19.9	16.0	42.0	10.4
FS-57	Nugget Sandstone	~~2.7~~	~~1.2~~	~~0.6~~	~~0.2~~	~~0.5~~	~~1.4~~	*2.2*	*10.3*	19.6	14.8	36.3	10.3
FS-58	Eolian/alluvial sand	0	0	0	0	0	0	0	*5.8*	*13.9*	15.8	58.3	6.2
FS-59	Nugget Sandstone	0	0	0	0	0	0	~~0.5~~	*1.6*	*7.8*	18.0	63.4	8.7
FS-60	Nugget Sandstone	0	0	0	0	0	0	~~1.3~~	*5.5*	*9.8*	11.8	53.9	17.7

Notes:

~~Strikethrough~~ indicates that approximately 50% or more of the material retained in the sieve designation are aggregated grains, thus the reported percentage is unrepresentative.

Italics indicates that approximately 10 to 50% of the material retained are aggregated grains.

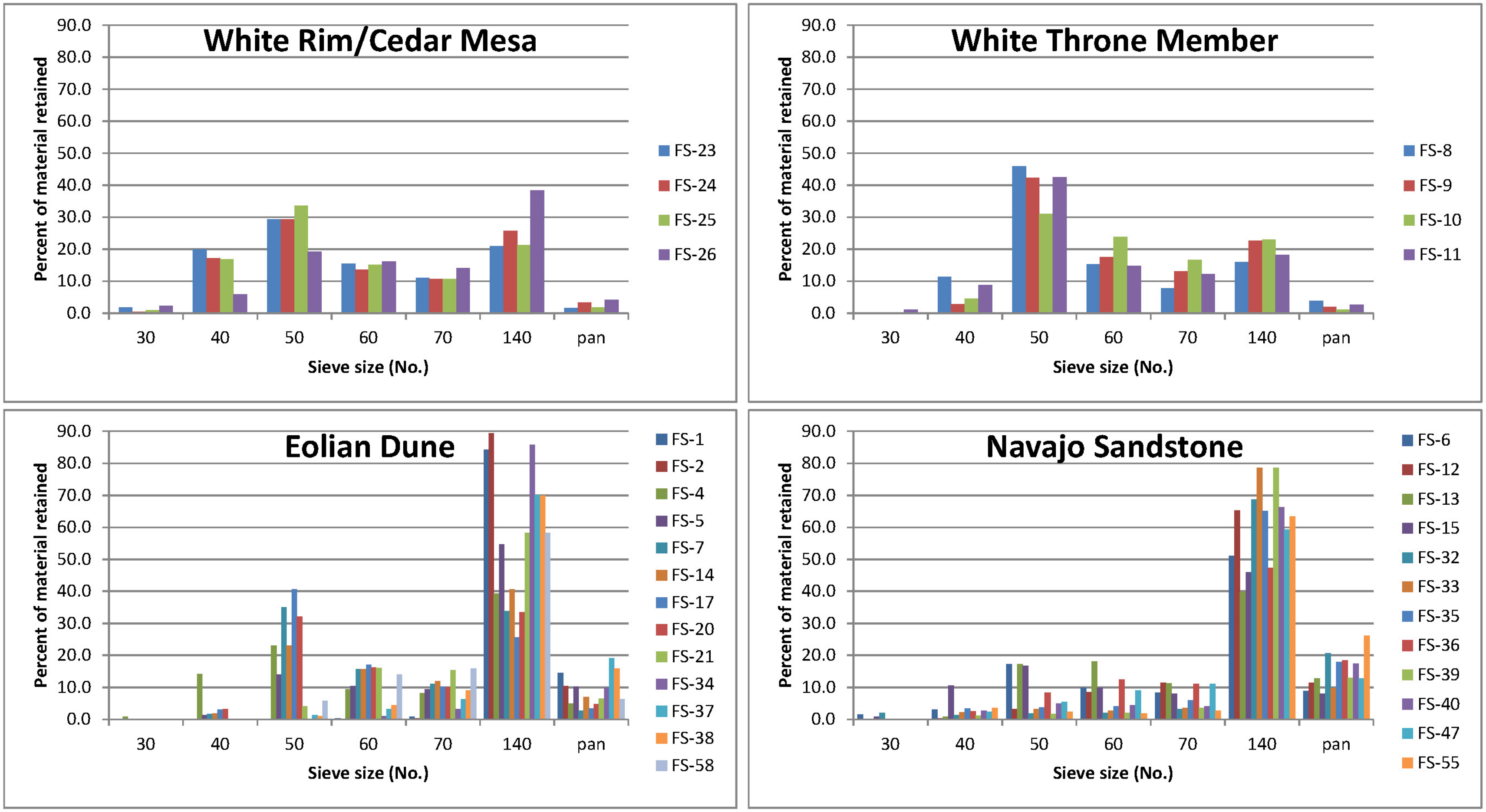

Figure 6 *. Histograms showing size distribution of grains of frac sand samples from selected geologic units with multiple samples.*

material retained on the no. 30 sieve. However, the 30/50, 40/60, or 40/70 frac sand designations could potentially be produced from a number of units given our sieve results. Also, plenty of the less desirable 70/140 material could be produced.

As noted in table 4, we observed the presence of aggregated grains (grains that did not disaggregate during sample preparation) in a number of size fractions, which skews the results to some degree. Table 4 reports which sieve samples contained a significant percentage of aggregate grains, so those can be taken into account when reviewing the results. Photomicrographs from appendix B also illustrate, to some degree, aggregated grain content. Generally, aggregated grains are in samples from consolidated rock units, although a few unconsolidated Quaternary units also contained a notable portion of aggregated grains (FS-34, 37, 38, and 58).

Sphericity and Roundness

Table 5 presents sphericity and roundness results of selected size fractions from a number of samples. All the evaluated samples met the minimum recommended sphericity of 0.6 from the Krumbein/Sloss chart; however, many samples did not meet the minimum recommended roundness of 0.6. Samples from the following geologic units met both requirements: White Rim/Cedar Mesa Sandstones, Nugget Sandstone, Navajo Sandstone, White Throne Member of the Temple Cap Formation, Thousand Pockets Tongue of the Page Sandstone, Carmel Formation, capping sandstone of the Wahweap Formation, and eolian sand. Variability exists within these units; for instance, only one sample from the White Rim/Cedar Mesa samples met the 0.6 roundness recommendation—most samples from that unit had a roundness of 0.5. Table 5 also reports the standard deviation about the mean to show variability of sphericity and roundness within the size fractions selected for evaluation. On average, the standard deviation for roundness is higher than that for sphericity.

Because only selected size fractions were evaluated for sphericity and roundness, the reported results should not be considered representative of the entire sample. Generally speaking, the smaller size fractions are more angular than larger size fractions. Photomicrographs of grains from various size fractions from appendix B show this observation. As previously noted, aggregated grains were not evaluated for roundness and sphericity.

Friability

Friability was quite variable among the samples we collected, and was also commonly variable within a single sampled section. A qualitative estimate of friability for each frac sand sample is presented in table 2. Some of the more consistently friable units we sampled are the Navajo Sandstone in southwestern Utah and the White Throne Member of the Temple Cap Formation.

Most of the samples we collected were from weathered outcrop, which may be unrepresentative of fresh exposures of rock that would be encountered during mining. We collected one sample of Navajo Sandstone at a relatively fresh road cut (FS-32). The Navajo Sandstone at this location was generally more competent than most, if not all, of the other Navajo Sandstone that we sampled. This sample required additional effort to disaggregate prior to sieving. This observation suggests that additional sampling and characterization of fresh rock from the rock units with the best potential is needed to determine ultimate suitability.

Table 4 shows that a number of samples did not disaggregate completely during sample preparation. Large amounts of aggregated grains observed in a sample are a potential indication of less friable rock.

Table 5 *. Sphericity and roundness of frac sand samples. Red indicates values below the acceptable limit.*

Sample	Geological Unit	Sphericity	Standard Deviation Sphericity	Roundness	Standard Deviation Roundness
FS-1 No. 140	Eolian sand	0.6	0.17	0.3	0.14
FS-2 No. 140	Eolian sand	0.6	0.18	0.3	0.24
FS-4 No. 50	Eolian sand	0.7	0.09	0.8	0.12
FS-5 No. 50	Eolian sand	0.7	0.16	0.7	0.19
FS-6 No. 50	Navajo Sandstone	0.7	0.19	0.7	0.14
FS-7 No. 50	Eolian sand	0.7	0.15	0.6	0.19
FS-8 No. 50	White Throne Mbr.	0.6	0.16	0.6	0.16
FS-9 No. 50	White Throne Mbr.	0.7	0.16	0.6	0.21
FS-10 No. 50	White Throne Mbr.	0.7	0.11	0.8	0.10
FS-11 No. 50	White Throne Mbr.	0.7	0.15	0.7	0.16
FS-12 No. 70	Navajo Sandstone	0.7	0.16	0.5	0.10
FS-13 No. 60	Navajo Sandstone	0.7	0.11	0.6	0.19
FS-14 No. 50	Eolian sand	0.7	0.12	0.7	0.13
FS-15 No. 50	Navajo Sandstone	0.8	0.10	0.7	0.16
FS-16 No. 50	Carmel Fm.	0.7	0.16	0.7	0.14
FS-17 No. 50	Eolian sand	0.7	0.16	0.6	0.13
FS-18 No. 50	Thousand Pockets	0.7	0.14	0.7	0.18
FS-19 No. 50	Thousand Pockets	0.7	0.12	0.7	0.15
FS-20 No. 50	Eolian sand	0.7	0.18	0.7	0.16
FS-21 No. 60	Eolian sand	0.7	0.11	0.5	0.18
FS-23 No. 50	White Rim/Cedar Mesa	0.8	0.09	0.5	0.15
FS-24 No. 50	White Rim/Cedar Mesa	0.7	0.13	0.5	0.20
FS-25 No. 50	White Rim/Cedar Mesa	0.7	0.13	0.5	0.19
FS-26 No. 50	White Rim/Cedar Mesa	0.8	0.12	0.6	0.20
FS-27 No. 70	Sego Sandstone	0.7	0.14	0.3	0.17
FS-29 No. 70	Castlegate Sandstone	0.7	0.13	0.3	0.18
FS-30 No. 50	Dakota Sandstone	0.6	0.15	0.4	0.20
FS-31 No. 140	Wingate Sandstone	0.6	0.17	0.4	0.17
FS-32 No. 140	Navajo Sandstone	0.7	0.16	0.5	0.16
FS-33 No. 140	Navajo Sandstone	0.7	0.14	0.4	0.15
FS-34 No. 140	Eolian sand	0.7	0.17	0.4	0.16
FS-35 No. 70	Navajo Sandstone	0.6	0.19	0.5	0.14
FS-36 No. 60	Navajo Sandstone	0.7	0.12	0.6	0.13
FS-37 No. 140	Eolian sand	0.6	0.17	0.5	0.18
FS-38 No. 70	Eolian sand	0.6	0.14	0.4	0.21
FS-39 No. 140	Navajo Sandstone	0.6	0.15	0.4	0.20
FS-40 No. 140	Navajo Sandstone	0.7	0.10	0.4	0.17
FS-43 No. 50	Wahweap Fm.	0.7	0.11	0.6	0.19
FS-44 No. 60	Wahweap Fm.	0.7	0.10	0.5	0.16
FS-45 No. 60	Wahweap Fm.	0.7	0.09	0.5	0.25
FS-45 No. 70	Wahweap Fm.	0.7	0.11	0.4	0.17
FS-46 No. 50	Wahweap Fm.	0.8	0.09	0.6	0.24
FS-47 No. 70	Navajo Sandstone	0.6	0.13	0.5	0.18
FS-52 No. 50	Mesaverde Group	0.6	0.14	0.2	0.11
FS-53 No. 60	Eolian sand	0.7	0.13	0.2	0.11
FS-56 No. 60	Nugget Sandstone	0.7	0.13	0.6	0.14
FS-57 No. 60	Nugget Sandstone	0.7	0.14	0.6	0.14
FS-58 No. 60	Eolian/alluvial sand	0.7	0.17	0.6	0.17
FS-59 No. 70	Nugget Sandstone	0.6	0.12	0.5	0.15
FS-60 No. 60	Nugget Sandstone	0.7	0.16	0.6	0.19

Note:
Aggregated grains were not considered during evaluation of sphericity and roundness.

CONCLUSIONS

Results from the tests performed on the frac sand samples are summarized in table 6 with an assigned rating of overall frac sand suitability for each sample (see also plate 1). Three geologic units stand out as having the highest potential based on our testing results: White Rim/Cedar Mesa Sandstones, White Throne Member of the Temple Cap Formation, and some eolian sand deposits. One sample of the Navajo Sandstone (out of 13) also received a "high suitability" rating; however, this sample (FS-15) may be from the Lamb Point Tongue of the Navajo Sandstone in western Kane County. The samples from the White Rim/Cedar Mesa Sandstones showed the highest suitability for a 30/50 sized proppant. However, most of these samples were slightly low in roundness (table 5), and friability was variable where we sampled it. We sampled the White Rim/ Cedar Mesa Sandstones in the San Rafael Swell where the two sandstone units are undifferentiated in available geologic mapping. Figure 7 shows where the unit crops out and where SITLA surface or mineral rights are coincident with the unit.

We sampled the White Throne Member of the Temple Cap Formation in eastern Kane County where it is exposed in a number of SITLA properties (figure 8). The characteristics of the White Throne Member suggest that it may be a good candidate for frac sand usage, but for most samples, it had a low amount of material retained on the no. 40 sieve, suggesting that it might be better suited for a 40/70 proppant product. Some of the most promising results for a 40/70 product were from unconsolidated eolian sands in southwestern Utah. Five samples from Washington and Kane Counties received a "high suitability" rating, and one sample had a significant fraction of material retained on the no. 40 sieve. The eolian sands have the obvious benefit of being unconsolidated and are widespread in southwestern Utah. Figures 8, 9, and 10 show a number of areas where the eolian units coincide with SITLA property. Additional sampling and characterization of the eolian units would help delineate the best and largest deposits.

Figure 11 shows the Nugget's distribution in the area around Vernal. Although not having the highest potential, the Nugget Sandstone may deserve additional investigation due to its proximity to the oil and gas-producing Uinta Basin. In some of the areas in the Uinta Basin where we sampled it, the Nugget Sandstone was quite friable and some samples had a reasonable amount of material retained on the no. 50 sieve. The size fractions of Nugget we analyzed all showed above 94% SiO_2, and one sample showed 96% SiO_2. Given the high percentage that transportation contributes to overall frac sand cost, a local source would be very beneficial from a cost perspective.

The Navajo Sandstone is another unit of interest; however, the SiO_2 content of the Navajo was consistently lower than the other high-potential units. Also, the best Navajo Sandstone was in southwest Utah as the Navajo in southeast Utah was generally too fine grained. Based on results from sample FS-15, the Lamb Point Tongue of the Navajo Sandstone may deserve additional investigation (figure 8). Lenses of the capping sandstone of the Wahweap Formation may be suitable for frac sand, but significantly more detailed characterization of the unit would likely be required to find the best areas.

Of the highest potential units, the White Rim/Cedar Mesa Sandstone is closest to rail (plate 1), but also has the disadvantage of being in a popular recreational area. The White Throne Member and eolian sands in southwest Utah we examined are not close to rail, but are close to good access roads.

Table 6 *. Summary of frac sand sample suitability.*

	High Suitability	Medium Suitability	Low Suitability
	1	2	3
Criteria:			
Chemistry[1]	>97% SiO_2	95-97% SiO_2	<95% SiO_2
30/50	>10% retained on no. 40	5-10% retained on no. 40	<5% retained on no. 40
40/70	>15% retained on no. 50	10-15% retained on no. 50	<10% retained on no. 50
Roundness[2]	0.6 or higher	0.5	0.4 or lower
Friability	Very friable or unconsolidated	Moderately friable	Slightly or not friable

Sample No.	Chemistry	30/50	40/70	Roundness	Friability	Overall Suitability[3]	Geologic Unit
FS-4	1	1	1	1	1	1	Eolian sand
FS-7	1	3	1	1	1	1	Eolian sand
FS-14	1	3	1	1	1	1	Eolian sand
FS-17	1	3	1	1	1	1	Eolian sand
FS-20	1	3	1	1	1	1	Eolian sand
FS-15	2	1	1	1	1	1	Navajo Sandstone
FS-23	1	1	1	2	2	1	White Rim/Cedar Mesa
FS-24	1	1	1	2	2	1	White Rim/Cedar Mesa
FS-25	1	1	1	2	2	1	White Rim/Cedar Mesa
FS-8	1	1	1	1	1	1	White Throne Mbr.
FS-9	1	3	1	1	1	1	White Throne Mbr.
FS-10	1	3	1	1	1	1	White Throne Mbr.
FS-11	1	2	1	1	1	1	White Throne Mbr.
FS-5	1	3	2	1	1	2	Eolian sand
FS-6	2	3	1	1	1	2	Navajo Sandstone
FS-13	2	3	1	1	1	2	Navajo Sandstone
FS-56	2	3	2 (?)	1	1	2	Nugget Sandstone
FS-18	2	3	1	1	1	2	Thousand Pockets
FS-19	2	3	1	1	1	2	Thousand Pockets
FS-43	1	3	1	1	2	2	Wahweap Fm.
FS-44	1	3	2	2	2	2	Wahweap Fm.
FS-26	1	3	1	1	2	2	White Rim/Cedar Mesa
FS-16	3	3	2	1	2	3	Carmel Fm.
FS-28	3	3	3	--	2	3	Castlegate Sandstone
FS-29	2	3	3	3	2	3	Castlegate Sandstone
FS-30	3	3	1	3	2	3	Dakota Sandstone
FS-50	--	--	--	--	3	3	Diamond Creek Sandstone
FS-54	--	--	--	--	3	3	Diamond Creek Sandstone
FS-22	3	3	3	--	2	3	Entrada Sandstone
FS-1	3	3	3	3	1	3	Eolian sand
FS-2	3	3	3	3	1	3	Eolian sand
FS-21	2	3	3	2	1	3	Eolian sand
FS-34	3	3	3	3	1	3	Eolian sand
FS-37	3	3	3	2	1	3	Eolian sand
FS-38	3	3	3	3	1	3	Eolian sand
FS-53	2	3	2	3	1	3	Eolian sand
FS-58	3	3	3	1	1	3	Eolian/alluvial Sand
FS-41	3	3	3	--	3	3	Ferron Sandstone
FS-52	2	2	1	3	1	3	Mesaverde Group
FS-12	2	3	3	2	1	3	Navajo Sandstone
FS-32	3	3	3	2	3	3	Navajo Sandstone
FS-33	3	3	3	3	1	3	Navajo Sandstone
FS-35	3	3	3	2	2	3	Navajo Sandstone
FS-36	3	3	3	1	2	3	Navajo Sandstone
FS-39	3	3	3	3	2	3	Navajo Sandstone
FS-40	3	3	3	3	3	3	Navajo Sandstone
FS-47	2	3	3	2	3	3	Navajo Sandstone
FS-49	--	--	--	--	3	3	Navajo Sandstone
FS-55	3	3	3	--	2	3	Navajo Sandstone
FS-57	3	3	3	1	2	3	Nugget Sandstone
FS-59	3	3	3	2	1	3	Nugget Sandstone
FS-60	3	3	3	1	2	3	Nugget Sandstone
FS-3	--	--	--	--	3	3	Queantoweap Sandstone

(continued)

Table 6 *. Summary of frac sand sample suitability.*

	High Suitability	Medium Suitability	Low Suitability
	1	2	3
Criteria:			
Chemistry[1]	>97% SiO_2	95-97% SiO_2	<95% SiO_2
30/50	>10% retained on no. 40	5-10% retained on no. 40	<5% retained on no. 40
40/70	>15% retained on no. 50	10-15% retained on no. 50	<10% retained on no. 50
Roundness[2]	0.6 or higher	0.5	0.4 or lower
Friability	Very friable or unconsolidated	Moderately friable	Slightly or not friable

Sample No.	Chemistry	30/50	40/70	Roundness	Friability	Overall Suitability[3]	Geologic Unit
FS-48	--	--	--	--	3	3	Queantoweap Sandstone
FS-27	3	3	3	3	1	3	Sego Sandstone
FS-51	3	3	2	--	3	3	Uinta Fm.
FS-42	--	--	--	--	3	3	Wahweap Fm.
FS-45	1	3	3	2	2	3	Wahweap Fm.
FS-46	2	3	3	1	2	3	Wahweap Fm.
FS-31	3	3	3	3	2	3	Wingate Sandstone

[1]Primarily based on analysis of selected size fraction rather than whole-rock analysis; Table 3 shows which size fractions were analyzed for chemistry.

[2]Sphericity is not included in the matrix because all samples evaluated met the sphericity recommendation; Table 5 shows which size fractions were evaluated for roundness.

[3]Overall suitability is based on the average of all characteristics. If the average is 1 to 1.5 the overall suitability is 1, if the average is above 1.5 to 2.0 the overall suitability is 2, if the average is above 2.0 the overall suitability is 3. Although the Mesaverde Group average is below 2, we gave it a low suitability rating because of its low roundness.

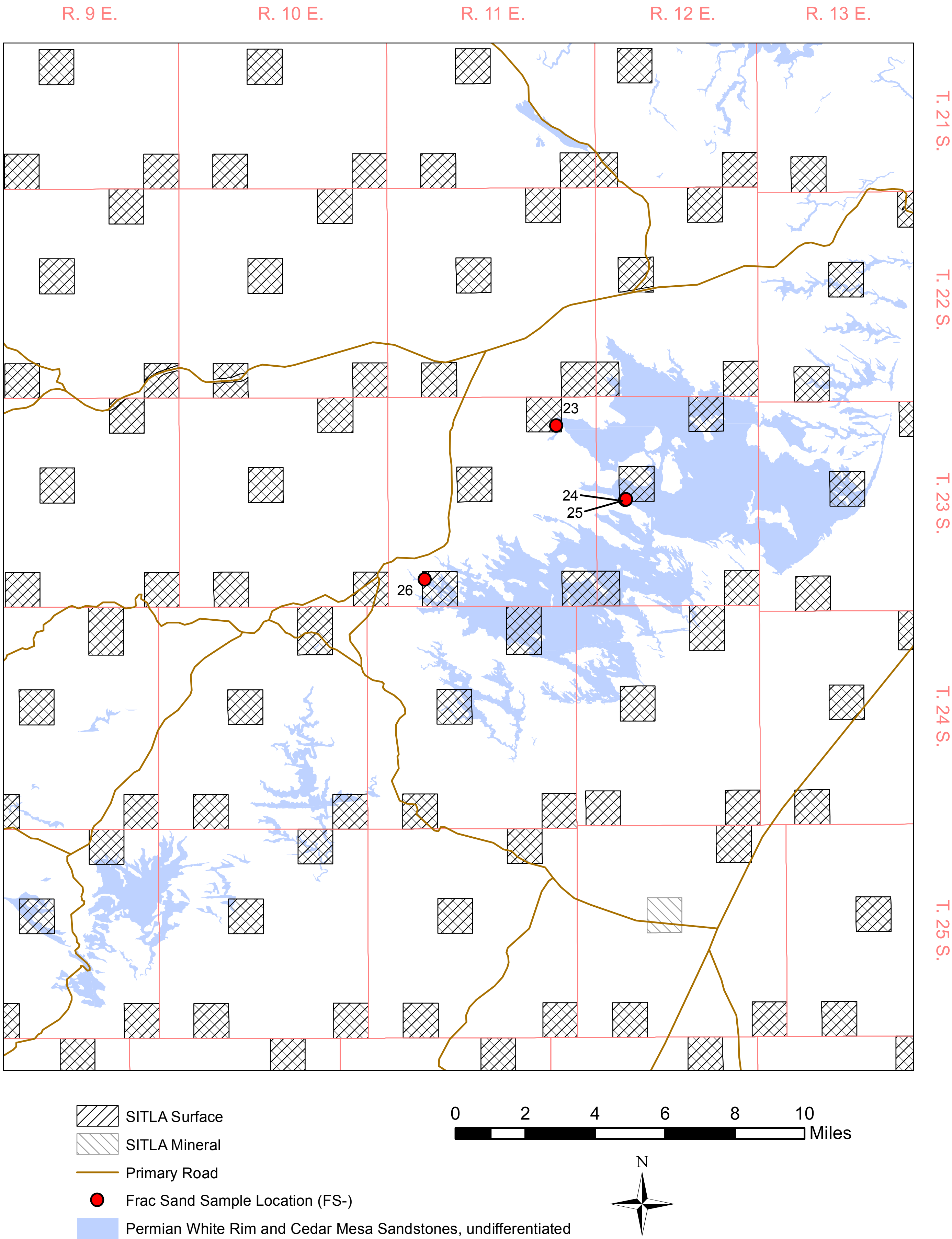

Figure 7. *SITLA property and geologic units with frac sand potential in Emery County. Geology is from Doelling (2002b).*

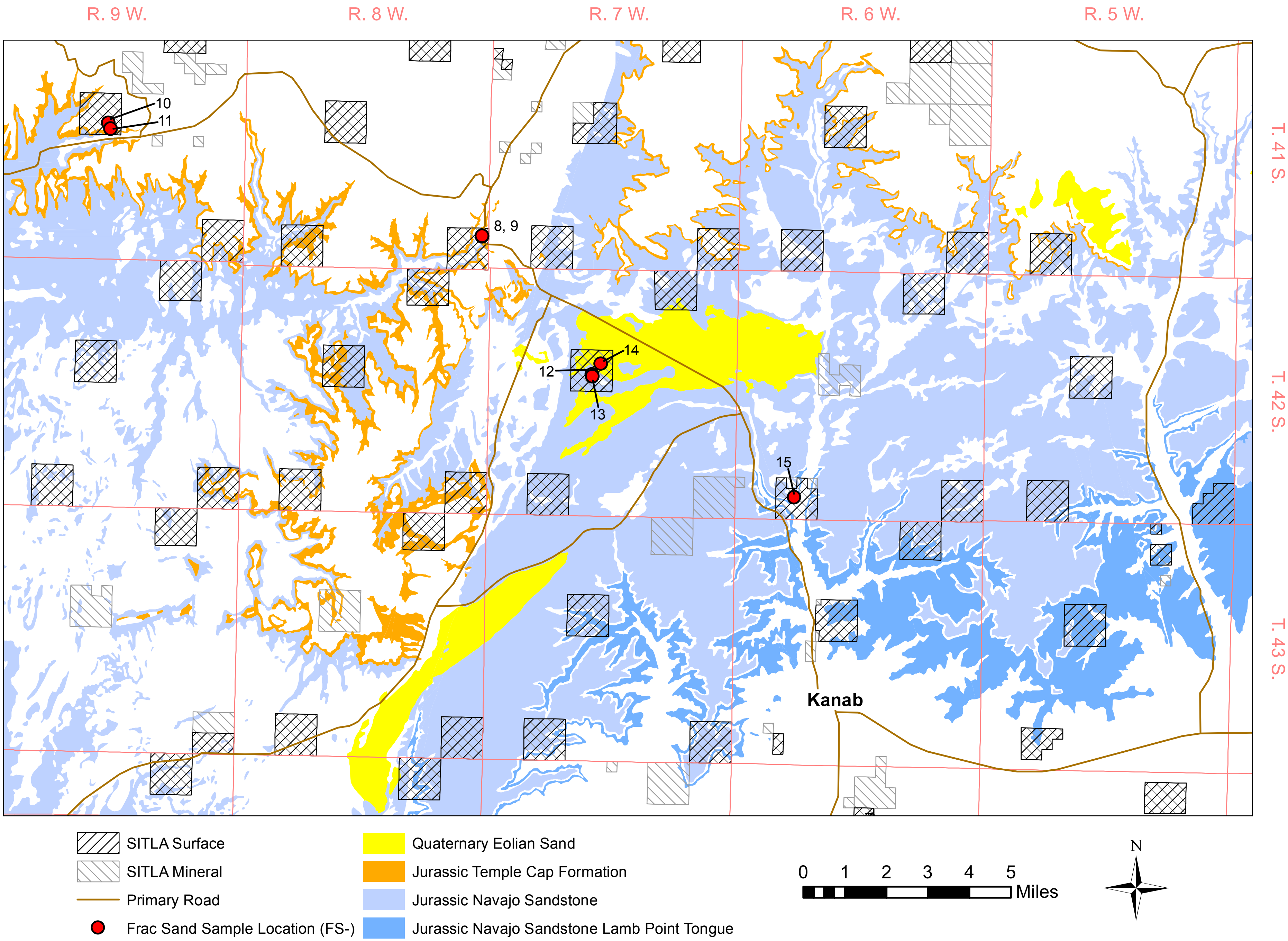

Figure 8. *SITLA property and geologic units with frac sand potential in western Kane County. Geology is from Doelling (2008).*

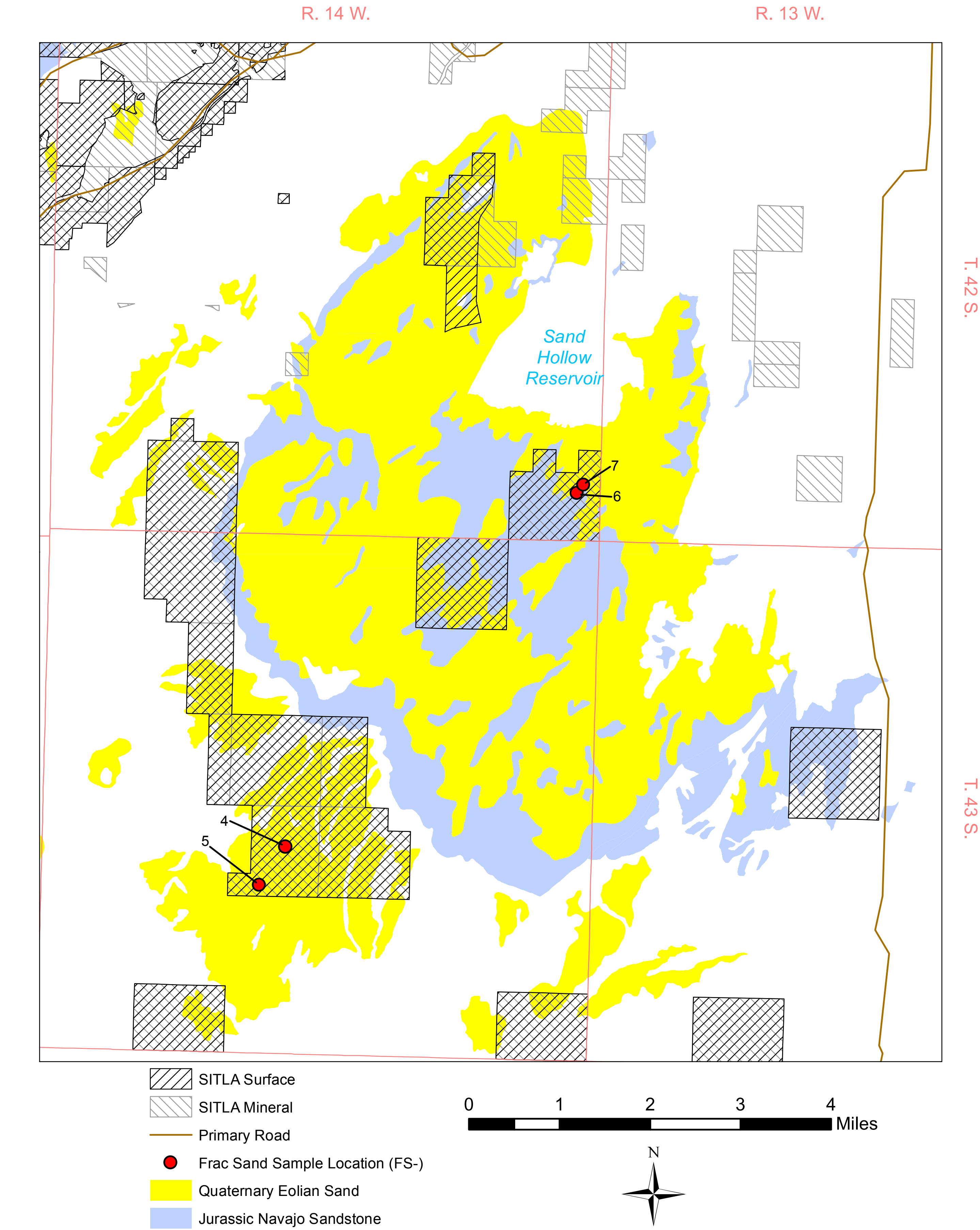

Figure 9. *SITLA property and geologic units with frac sand potential in southern Washington County. Geology is from Biek and others (2010).*

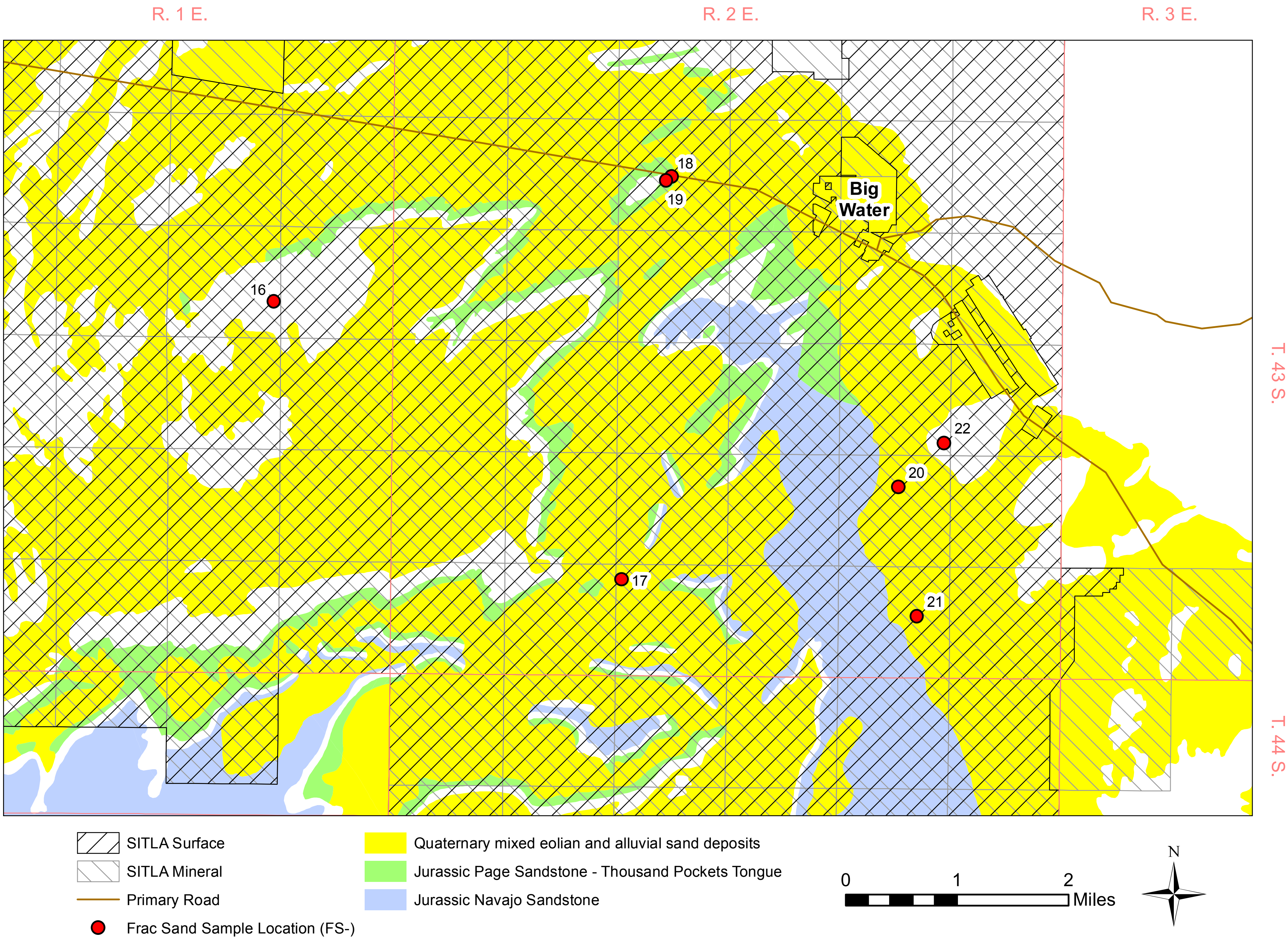

Figure 10. *SITLA property and geologic units with frac sand potential in southeastern Kane County. Geology is from Doelling and Willis (2006).*

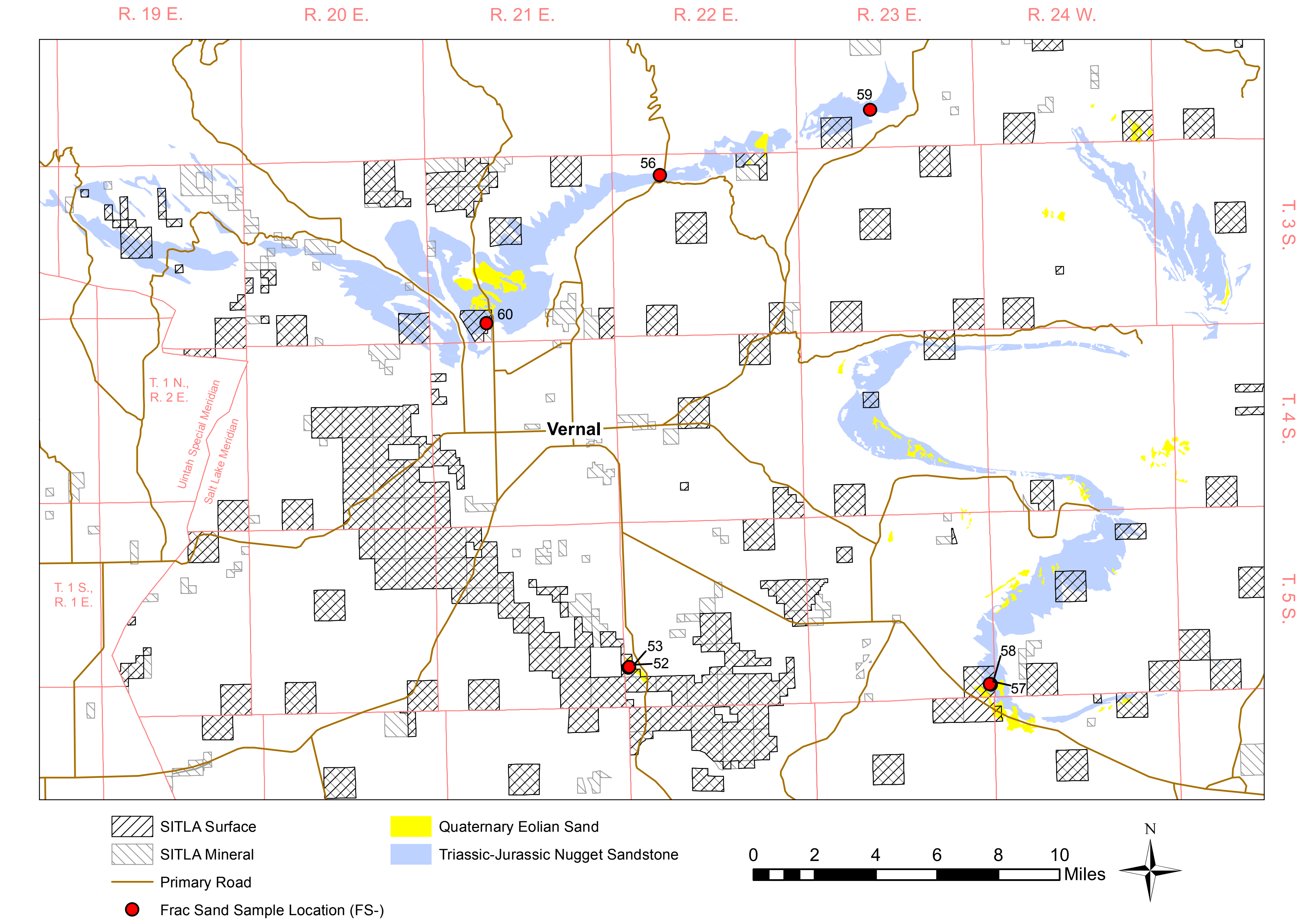

Figure 11. *SITLA property and geologic units with frac sand potential near Vernal. Geology is from Sprinkel (2006 and 2007).*

Additional work, particularly crush resistance testing, will be necessary to determine if any of the deposits are ultimately suitable for use as frac sand. Also, determining whether units that are very friable at the surface are also friable in fresh exposures will be important. Additional testing of specific favorable units is warranted based on results from this study, particularly for eolian sands in southwest Utah, and possibly the White Throne Member of the Temple Cap Formation and the White Rim/Cedar Mesa Sandstones. The Nugget Sandstone in the Uinta Basin may also deserve some additional investigation.

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APPENDIX A.

Raw sieve analysis data

Appendix A *. Raw sieve analysis data.*

Sample No.		Material Retained on Sieve No. 8	12	16	18	20	Primary sizes 30	40	Secondary sizes 50	60	70	Marginal size 140	pan	total
FS-1														
	(lbs)	0	0	0	0	0	0	0	0.004	0.018	0.058	5.432	0.934	6.446
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.28	0.90	84.27	14.49	100.00
FS-2														
	(lbs)	0	0	0	0	0	0	0	0	0	0.018	5.622	0.65	6.29
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	89.38	10.33	100.00
FS-4														
	(lbs)	0	0	0	0	0	0.038	0.61	0.996	0.408	0.354	1.698	0.214	4.318
	(%)	0.00	0.00	0.00	0.00	0.00	0.88	14.13	23.07	9.45	8.20	39.32	4.96	100.00
FS-5														
	(lbs)	0	0	0	0	0	0	0.066	0.724	0.54	0.482	2.814	0.528	5.154
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	1.28	14.05	10.48	9.35	54.60	10.24	100.00
FS-6														
	(lbs)	0	0	0	0	0	0.058	0.124	0.692	0.398	0.334	2.038	0.354	3.998
	(%)	0.00	0.00	0.00	0.00	0.00	1.45	3.10	17.31	9.95	8.35	50.98	8.85	100.00
FS-7														
	(lbs)	0	0	0	0	0	0	0.07	1.402	0.628	0.448	1.356	0.11	4.014
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	1.74	34.93	15.65	11.16	33.78	2.74	100.00
FS-8														
	(lbs)	0	0	0	0	0	0	0.142	0.572	0.19	0.096	0.198	0.048	1.246
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	11.40	45.91	15.25	7.70	15.89	3.85	100.00
FS-9														
	(lbs)	0	0	0	0	0	0	0.05	0.78	0.322	0.24	0.416	0.034	1.842
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	2.71	42.35	17.48	13.03	22.58	1.85	100.00
FS-10														
	(lbs)	0	0	0	0	0	0	0.066	0.458	0.352	0.246	0.338	0.016	1.476
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	4.47	31.03	23.85	16.67	22.90	1.08	100.00
FS-11														
	(lbs)	0	0	0	0	0	0.044	0.338	1.644	0.57	0.472	0.706	0.098	3.872
	(%)	0.00	0.00	0.00	0.00	0.00	1.14	8.73	42.46	14.72	12.19	18.23	2.53	100.00
FS-12														
	(lbs)	0	0	0	0	0	0	0.01	0.09	0.24	0.322	1.836	0.32	2.818
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.35	3.19	8.52	11.43	65.15	11.36	100.00
FS-13														
	(lbs)	0	0	0	0	0	0	0.014	0.268	0.282	0.176	0.618	0.198	1.556

(continued)

Appendix A. *Raw sieve analysis data.*

	Material Retained on Sieve No.					Primary sizes		Secondary sizes			Marginal size		
Sample No.	**8**	**12**	**16**	**18**	**20**	**30**	**40**	**50**	**60**	**70**	**140**	**pan**	**total**
(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.90	17.22	18.12	11.31	39.72	12.72	100.00
FS-14													
(lbs)	0	0	0	0	0	0	0.062	0.762	0.518	0.396	1.346	0.232	3.316
(%)	0.00	0.00	0.00	0.00	0.00	0.00	1.87	22.98	15.62	11.94	40.59	7.00	100.00
FS-15													
(lbs)	0	0	0	0	0	0.018	0.24	0.376	0.222	0.18	1.038	0.182	2.256
(%)	0.00	0.00	0.00	0.00	0.00	0.80	10.64	16.67	9.84	7.98	46.01	8.07	100.00
FS-16													
(lbs)	0	0	0.178	0.084	0.066	0.118	0.098	0.206	0.16	0.14	0.632	0.124	1.806
(%)	0.00	0.00	9.86	4.65	3.65	6.53	5.43	11.41	8.86	7.75	34.99	6.87	100.00
FS-17													
(lbs)	0	0	0	0	0	0	0.15	1.99	0.838	0.498	1.26	0.17	4.906
(%)	0.00	0.00	0.00	0.00	0.00	0.00	3.06	40.56	17.08	10.15	25.68	3.47	100.00
FS-18													
(lbs)	0	0	0	0	0	0	0.106	0.34	0.194	0.176	0.696	0.046	1.558
(%)	0.00	0.00	0.00	0.00	0.00	0.00	6.80	21.82	12.45	11.30	44.67	2.95	100.00
FS-19													
(lbs)	0	0	0	0	0	0.072	0.076	0.894	0.542	0.536	1.296	0.246	3.662
(%)	0.00	0.00	0.00	0.00	0.00	1.97	2.08	24.41	14.80	14.64	35.39	6.72	100.00
FS-20													
(lbs)	0	0	0	0	0	0	0.108	1.056	0.534	0.33	1.1	0.156	3.284
(%)	0.00	0.00	0.00	0.00	0.00	0.00	3.29	32.16	16.26	10.05	33.50	4.75	100.00
FS-21													
(lbs)	0	0	0	0	0	0	0	0.112	0.446	0.43	1.62	0.178	2.786
(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.02	16.01	15.43	58.15	6.39	100.00
FS-22													
(lbs)	0	0	0	0	0	0	0.066	0.08	0.048	0.062	1.072	0.254	1.582
(%)	0.00	0.00	0.00	0.00	0.00	0.00	4.17	5.06	3.03	3.92	67.76	16.06	100.00
FS-23													
(lbs)	0	0	0	0	0	0.058	0.64	0.942	0.498	0.35	0.672	0.05	3.21
(%)	0.00	0.00	0.00	0.00	0.00	1.81	19.94	29.35	15.51	10.90	20.93	1.56	100.00
FS-24													
(lbs)	0	0	0	0	0	0.008	0.4	0.682	0.318	0.248	0.6	0.076	2.332
(%)	0.00	0.00	0.00	0.00	0.00	0.34	17.15	29.25	13.64	10.63	25.73	3.26	100.00
FS-25													

(continued)

Appendix A *. Raw sieve analysis data.*

	Material Retained on Sieve No.					Primary sizes		Secondary sizes			Marginal size		
Sample No.	**8**	**12**	**16**	**18**	**20**	**30**	**40**	**50**	**60**	**70**	**140**	**pan**	**total**
(lbs)	0	0	0	0	0	0.026	0.454	0.902	0.404	0.286	0.572	0.048	2.692
(%)	0.00	0.00	0.00	0.00	0.00	0.97	16.86	33.51	15.01	10.62	21.25	1.78	100.00
FS-26													
(lbs)	0	0	0	0	0	0.09	0.234	0.762	0.64	0.558	1.522	0.164	3.97
(%)	0.00	0.00	0.00	0.00	0.00	2.27	5.89	19.19	16.12	14.06	38.34	4.13	100.00
FS-27													
(lbs)	0	0	0	0	0	0	0.146	0.154	0.13	0.18	1.076	0.182	1.868
(%)	0.00	0.00	0.00	0.00	0.00	0.00	7.82	8.24	6.96	9.64	57.60	9.74	100.00
FS-28													
(lbs)	0	0	0	0	0	0.03	0.054	0.08	0.056	0.07	1.422	0.266	1.978
(%)	0.00	0.00	0.00	0.00	0.00	1.52	2.73	4.04	2.83	3.54	71.89	13.45	100.00
FS-29													
(lbs)	0	0	0	0	0	0	0.082	0.17	0.244	0.356	2.144	0.11	3.106
(%)	0.00	0.00	0.00	0.00	0.00	0.00	2.64	5.47	7.86	11.46	69.03	3.54	100.00
FS-30													
(lbs)	0	0	0	0	0	0.1	0.22	0.888	0.588	0.28	0.328	0.068	2.472
(%)	0.00	0.00	0.00	0.00	0.00	4.05	8.90	35.92	23.79	11.33	13.27	2.75	100.00
FS-31													
(lbs)	0	0	0	0	0	0.146	0.104	0.14	0.094	0.09	1.41	0.834	2.818
(%)	0.00	0.00	0.00	0.00	0.00	5.18	3.69	4.97	3.34	3.19	50.04	29.60	100.00
FS-32													
(lbs)	0	0	0	0	0	0.084	0.054	0.074	0.084	0.13	2.77	0.836	4.032
(%)	0.00	0.00	0.00	0.00	0.00	2.08	1.34	1.84	2.08	3.22	68.70	20.73	100.00
FS-33													
(lbs)	0	0	0	0	0	0	0.086	0.122	0.102	0.138	3.002	0.368	3.818
(%)	0.00	0.00	0.00	0.00	0.00	0.00	2.25	3.20	2.67	3.61	78.63	9.64	100.00
FS-34													
(lbs)	0	0	0	0	0	0	0	0.006	0.034	0.11	2.956	0.342	3.448
(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.99	3.19	85.73	9.92	100.00
FS-35													
(lbs)	0	0	0	0	0	0	0.126	0.14	0.158	0.224	2.474	0.682	3.804
(%)	0.00	0.00	0.00	0.00	0.00	0.00	3.31	3.68	4.15	5.89	65.04	17.93	100.00
FS-36													
(lbs)	0	0	0	0	0	0	0.082	0.278	0.41	0.368	1.566	0.61	3.314
(%)	0.00	0.00	0.00	0.00	0.00	0.00	2.47	8.39	12.37	11.10	47.25	18.41	100.00

(continued)

Appendix A. *Raw sieve analysis data.*

						Primary sizes		Secondary sizes			Marginal size		
	Material Retained on Sieve No.												
Sample No.	**8**	**12**	**16**	**18**	**20**	**30**	**40**	**50**	**60**	**70**	**140**	**pan**	**total**
FS-37													
(lbs)	0	0	0	0	0	0	0	0.048	0.12	0.228	2.564	0.698	3.658
(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	3.28	6.23	70.09	19.08	100.00
FS-38													
(lbs)	0	0	0	0	0	0	0	0.028	0.13	0.266	2.058	0.466	2.948
(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	4.41	9.02	69.81	15.81	100.00
FS-39													
(lbs)	0	0	0	0	0	0	0.046	0.06	0.078	0.134	2.934	0.482	3.734
(%)	0.00	0.00	0.00	0.00	0.00	0.00	1.23	1.61	2.09	3.59	78.58	12.91	100.00
FS-40													
(lbs)	0	0	0	0	0	0	0.106	0.19	0.172	0.158	2.528	0.666	3.82
(%)	0.00	0.00	0.00	0.00	0.00	0.00	2.77	4.97	4.50	4.14	66.18	17.43	100.00
FS-41													
(lbs)	0	0	0	0	0	0	0.23	0.146	0.164	0.082	0.4	1.454	2.476
(%)	0.00	0.00	0.00	0.00	0.00	0.00	9.29	5.90	6.62	3.31	16.16	58.72	100.00
FS-43													
(lbs)	0	0	0	0	0	0.02	0.118	0.72	0.574	0.384	0.866	0.144	2.826
(%)	0.00	0.00	0.00	0.00	0.00	0.71	4.18	25.48	20.31	13.59	30.64	5.10	100.00
FS-44													
(lbs)	0	0	0	0	0	0.016	0.048	0.612	0.706	0.704	2.164	0.168	4.418
(%)	0.00	0.00	0.00	0.00	0.00	0.36	1.09	13.85	15.98	15.93	48.98	3.80	100.00
FS-45													
(lbs)	0	0	0	0	0	0.018	0.028	0.16	0.2	0.23	1.01	0.208	1.854
(%)	0.00	0.00	0.00	0.00	0.00	0.97	1.51	8.63	10.79	12.41	54.48	11.22	100.00
FS-46													
(lbs)	0	0	0	0	0	0.054	0.076	0.258	0.256	0.26	1.368	0.454	2.726
(%)	0.00	0.00	0.00	0.00	0.00	1.98	2.79	9.46	9.39	9.54	50.18	16.65	100.00
FS-47													
(lbs)	0	0	0	0	0	0	0.058	0.132	0.218	0.268	1.438	0.312	2.426
(%)	0.00	0.00	0.00	0.00	0.00	0.00	2.39	5.44	8.99	11.05	59.27	12.86	100.00
FS-51													
(lbs)	0	0	0	0	0	0.122	0.22	0.292	0.206	0.15	0.406	0.18	1.576
(%)	0.00	0.00	0.00	0.00	0.00	7.74	13.96	18.53	13.07	9.52	25.76	11.42	100.00
FS-52													
(lbs)	0	0	0	0	0	0.018	0.08	0.374	0.22	0.114	0.356	0.14	1.302

(continued)

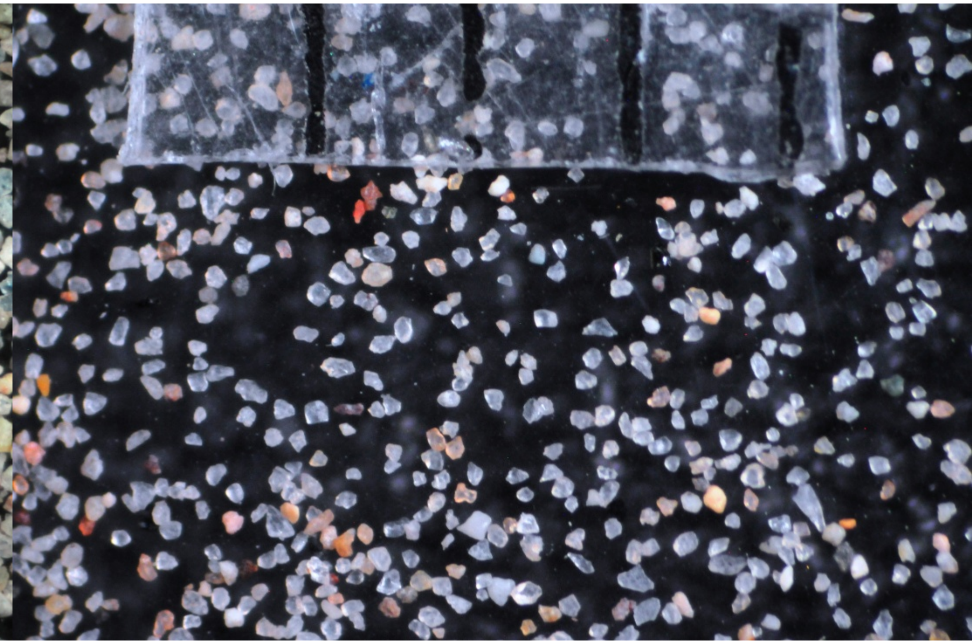
Appendix A . Raw sieve analysis data.

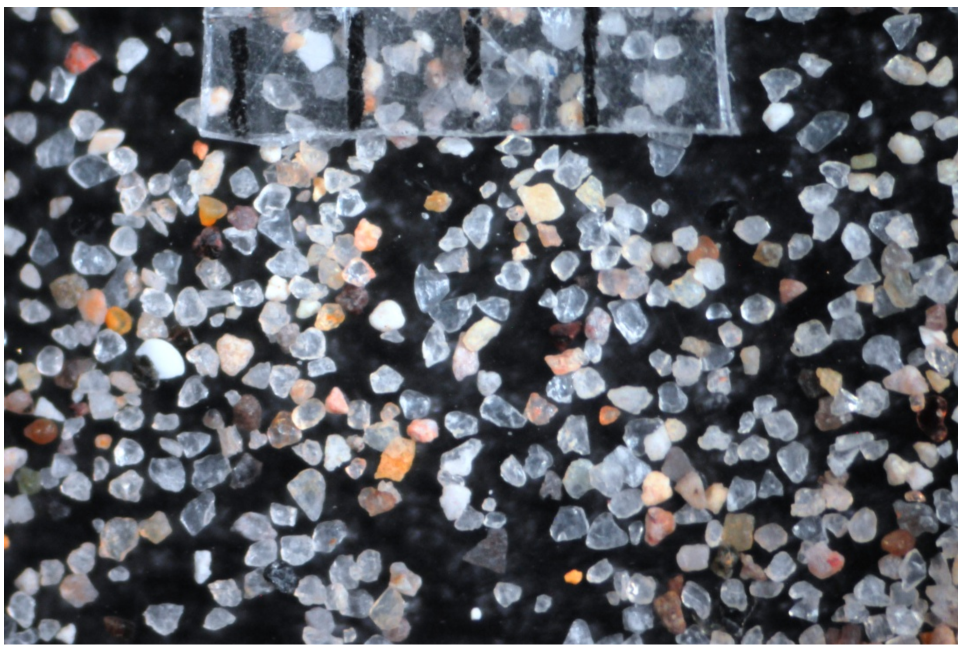
Sample No.		Material Retained on Sieve No. 8	12	16	18	20	Primary sizes 30	40	Secondary sizes 50	60	70	Marginal size 140	pan	total
	(%)	0.00	0.00	0.00	0.00	0.00	1.38	6.14	28.73	16.90	8.76	27.34	10.75	100.00
FS-53														
	(lbs)	0	0	0	0	0	0.004	0.044	0.538	0.774	0.626	1.81	0.2	3.996
	(%)	0.00	0.00	0.00	0.00	0.00	0.10	1.10	13.46	19.37	15.67	45.30	5.01	100.00
FS-55														
	(lbs)	0	0	0	0	0	0	0.04	0.028	0.022	0.032	0.724	0.298	1.144
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	3.50	2.45	1.92	2.80	63.29	26.05	100.00
FS-56														
	(lbs)	0	0	0	0	0	0	0.01	0.312	0.55	0.442	1.158	0.286	2.758
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.36	11.31	19.94	16.03	41.99	10.37	100.00
FS-57														
	(lbs)	0.054	0.024	0.012	0.004	0.01	0.028	0.044	0.204	0.39	0.294	0.722	0.204	1.99
	(%)	2.71	1.21	0.60	0.20	0.50	1.41	2.21	10.25	19.60	14.77	36.28	10.25	100.00
FS-58														
	(lbs)	0	0	0	0	0	0	0	0.12	0.29	0.33	1.214	0.13	2.084
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.76	13.92	15.83	58.25	6.24	100.00
FS-59														
	(lbs)	0	0	0	0	0	0	0.012	0.036	0.176	0.406	1.428	0.196	2.254
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	0.53	1.60	7.81	18.01	63.35	8.70	100.00
FS-60														
	(lbs)	0	0	0	0	0	0	0.026	0.106	0.19	0.228	1.042	0.342	1.934
	(%)	0.00	0.00	0.00	0.00	0.00	0.00	1.34	5.48	9.82	11.79	53.88	17.68	100.00

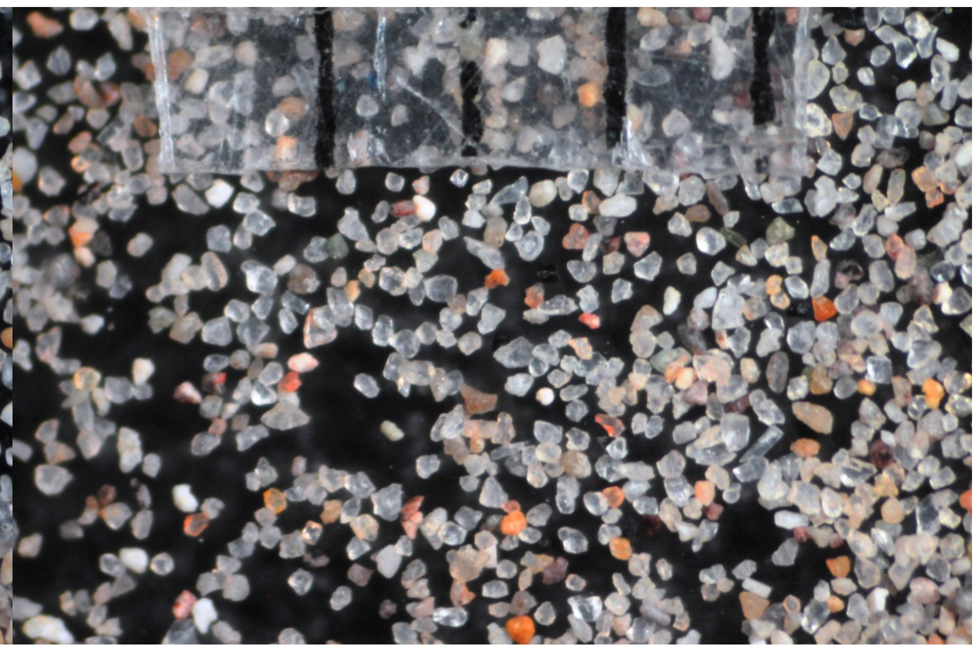
APPENDIX B.

Photomicrographs of selected size fractions of frac sand samples. Photomicrographs were taken at varying levels of magnification. Scale bar is in millimeters.


FS-1 No. 70


FS-1 No. 140


FS-2 No. 70


FS-2 No. 140

FS-4 No. 30

FS-4 No. 40

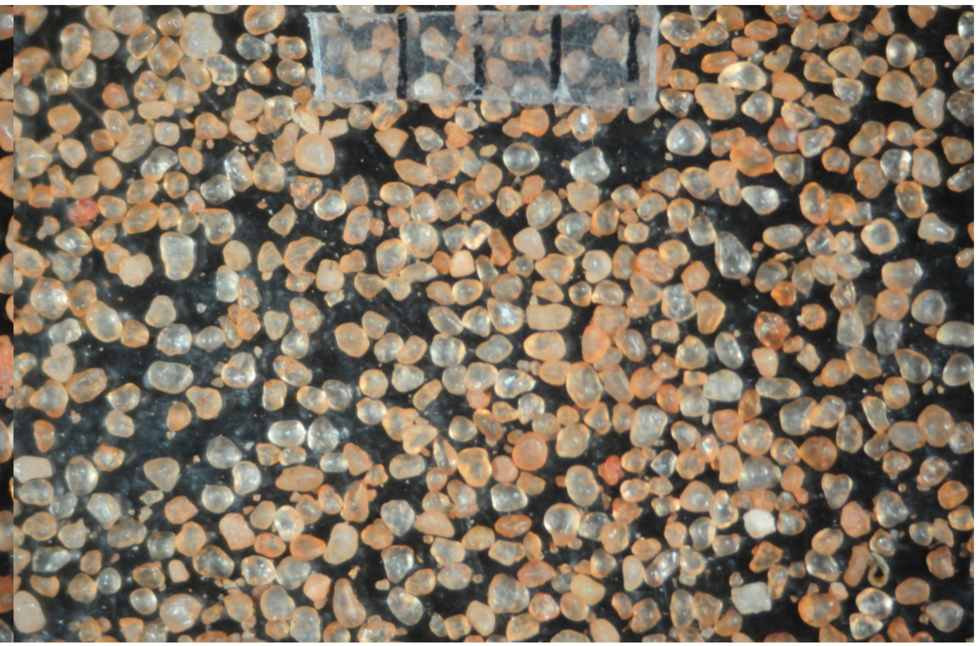
FS-4 No. 50

FS-4 No. 60

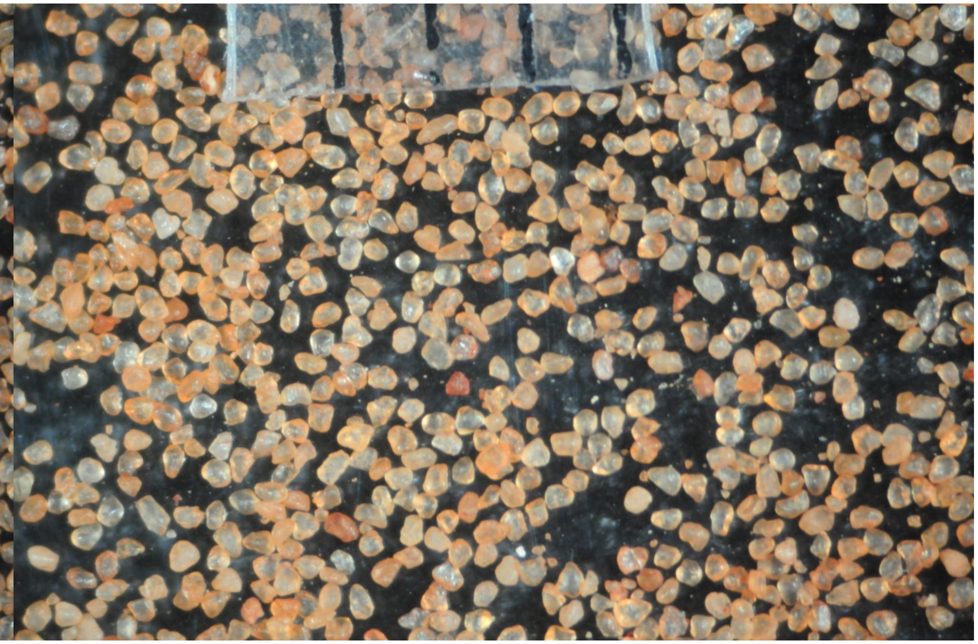

FS-4 No. 70


FS-4 No. 140


FS-5 No. 40


FS-5 No. 50

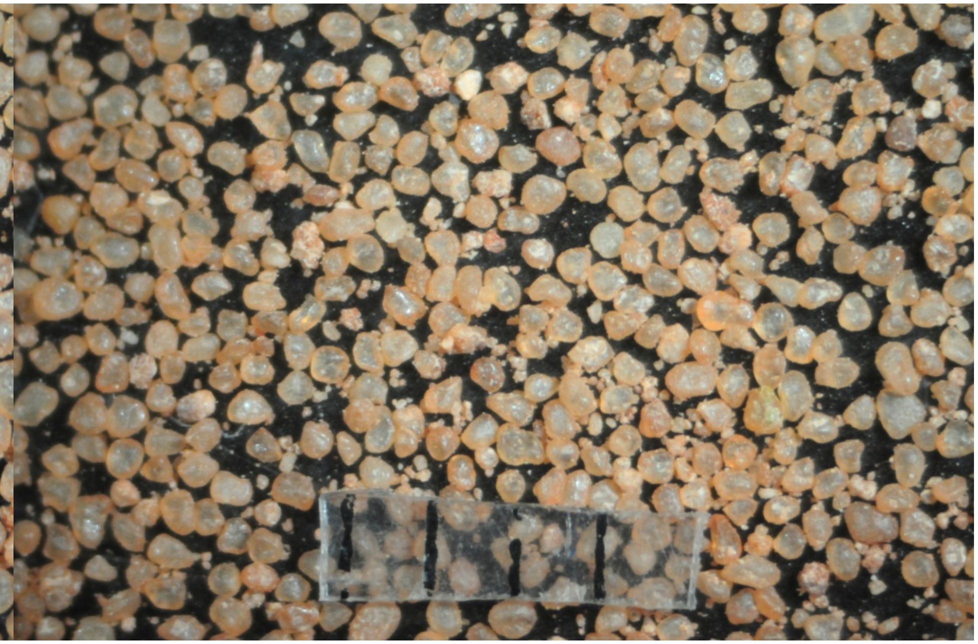

FS-5 No. 60

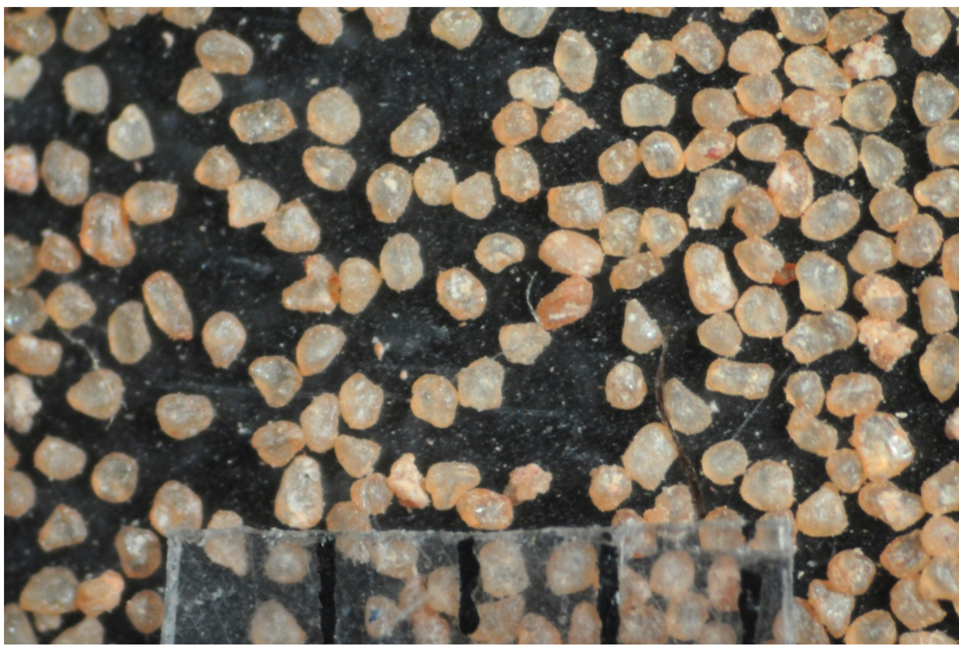

FS-5 No. 70

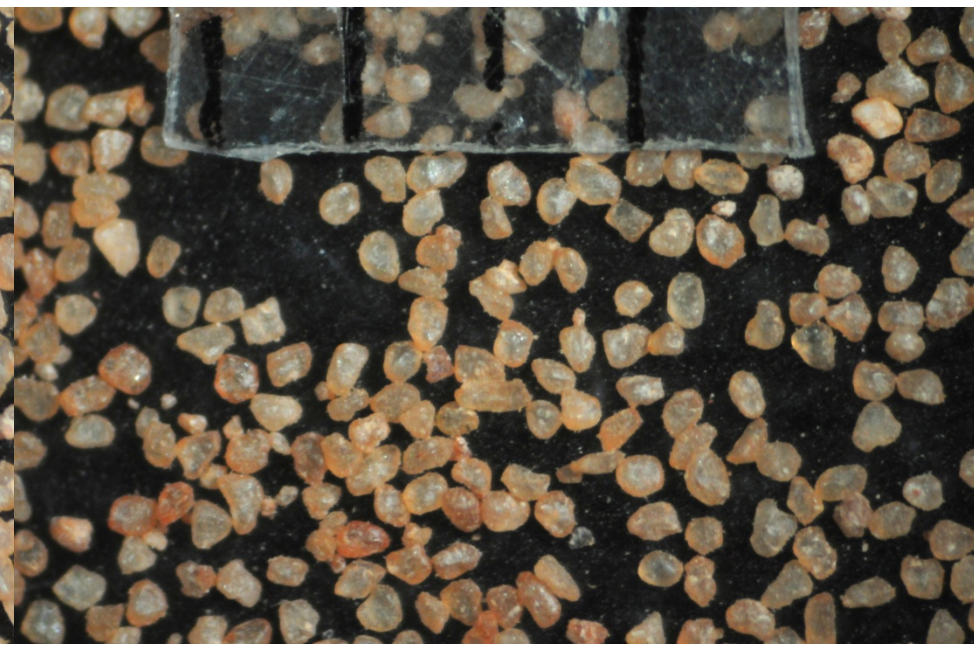

FS-5 No. 140

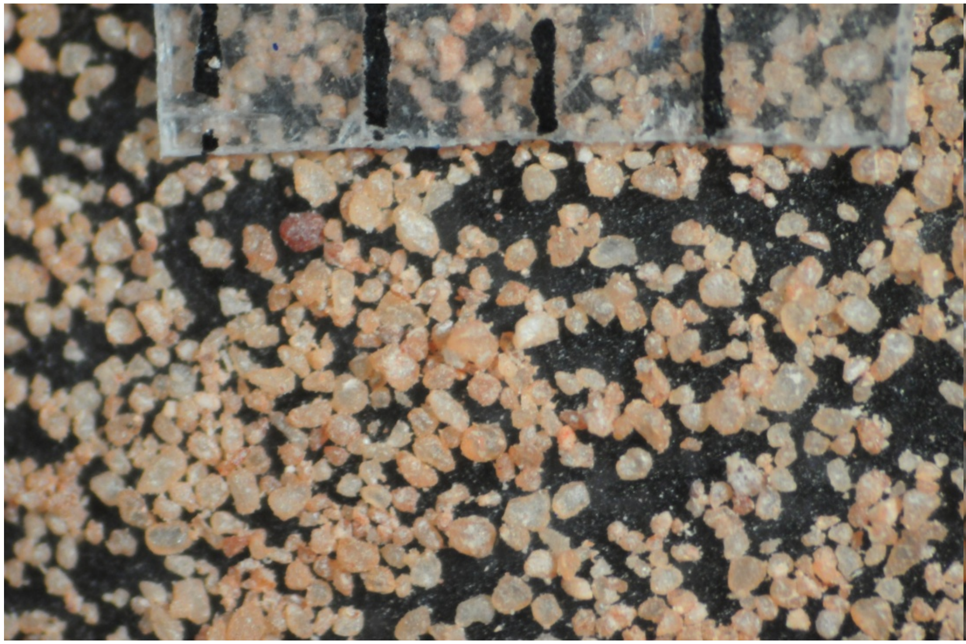

FS-6 No. 30


FS-6 No. 40


FS-6 No. 50


FS-6 No. 60


FS-6 No. 70

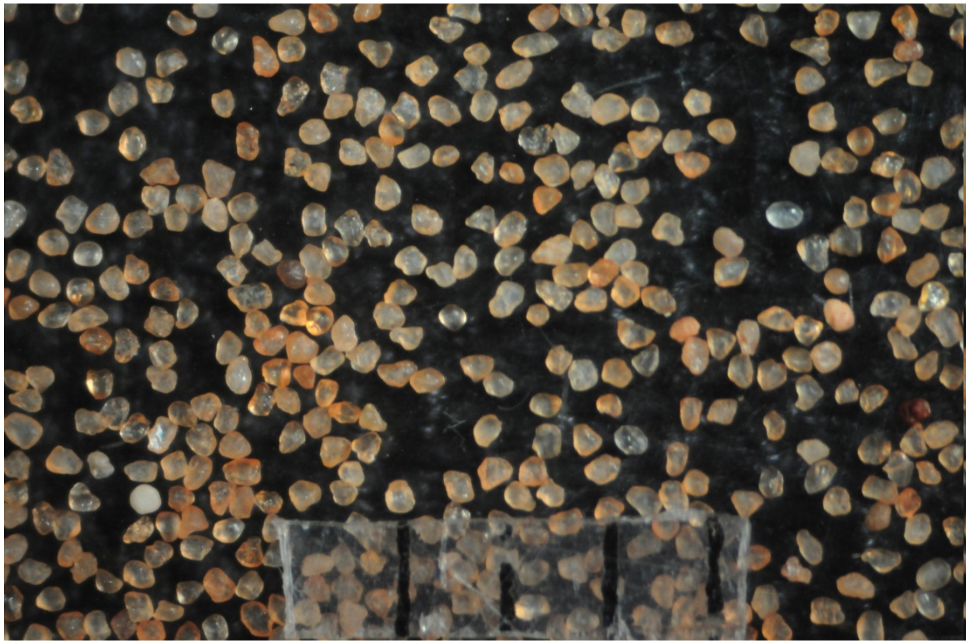


FS-6 No. 140

FS-7 No. 40

FS-7 No. 50

FS-7 No. 60


FS-7 No. 70

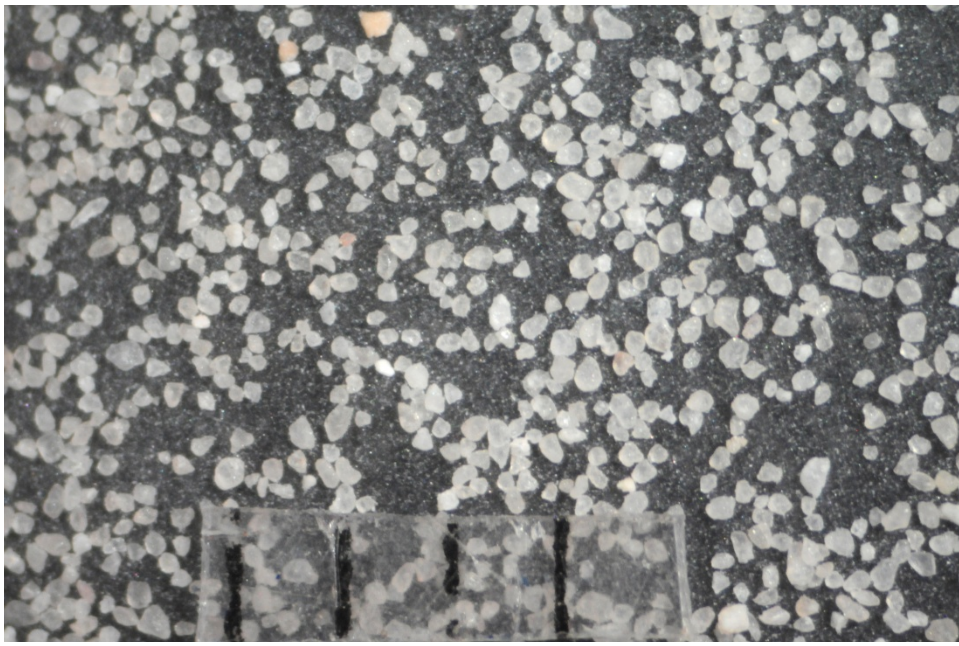

FS-7 No. 140

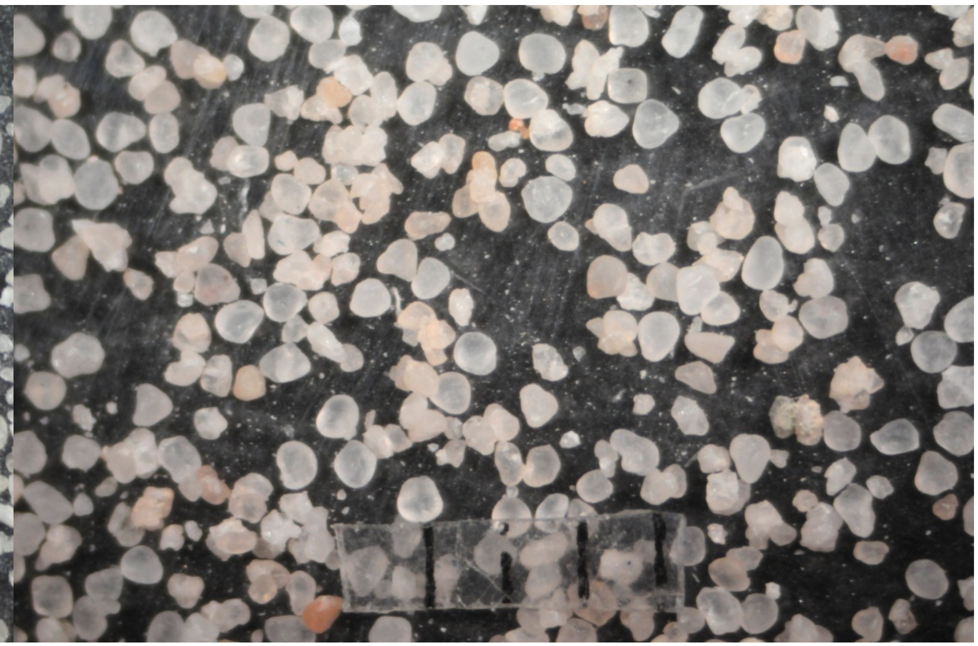

FS-8 No. 40

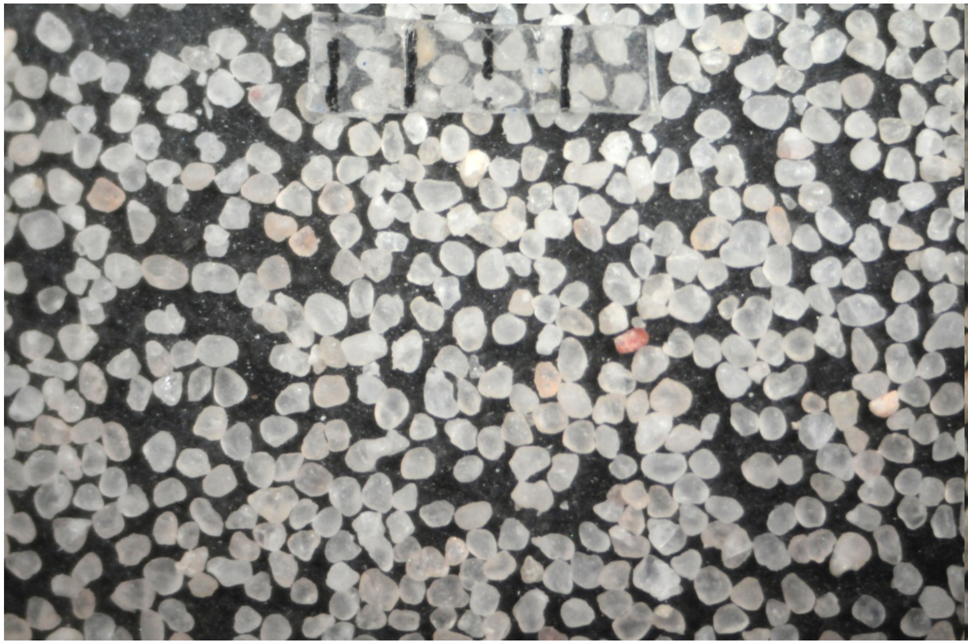

FS-8 No. 50


FS-8 No. 60


FS-8 No. 70


FS-8 No. 140


FS-9 No. 40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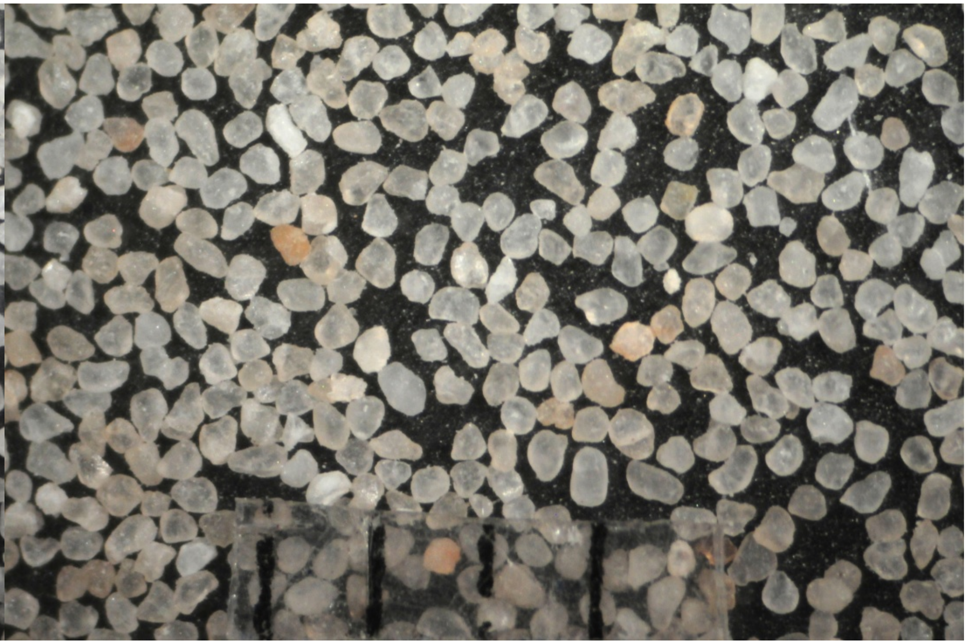
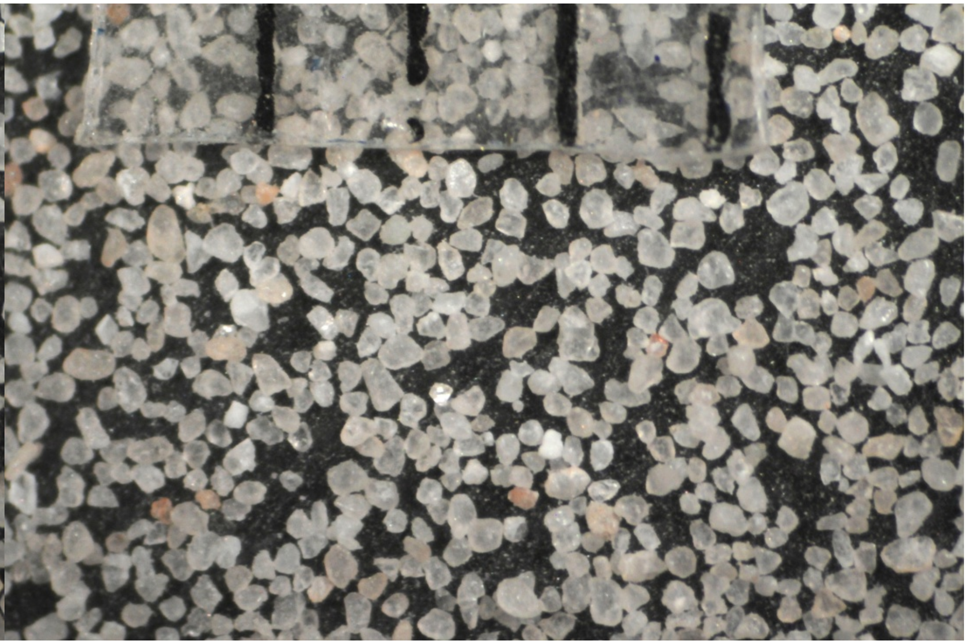
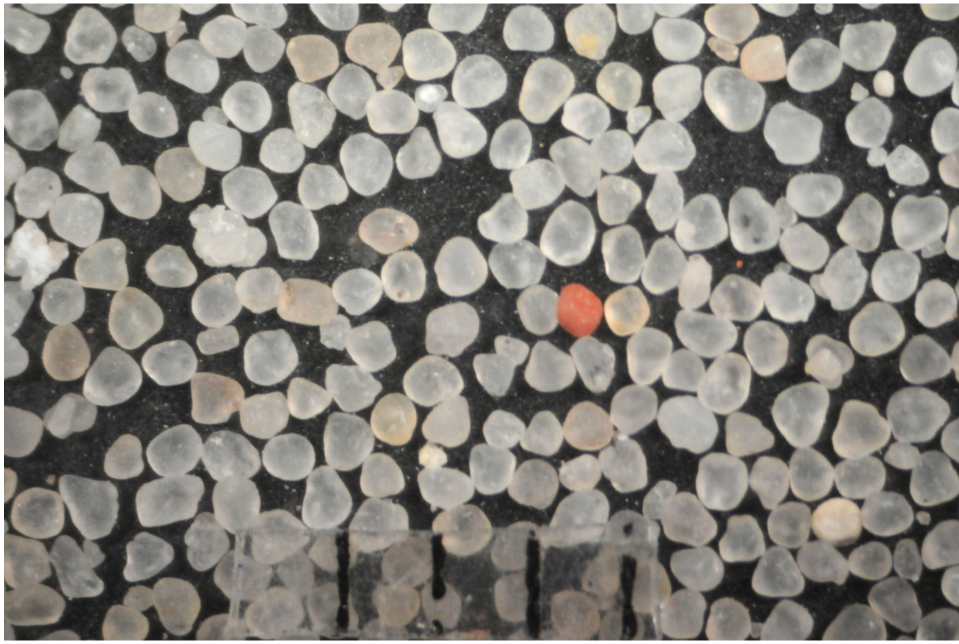

FS-9 No. 60


FS-9 No. 70

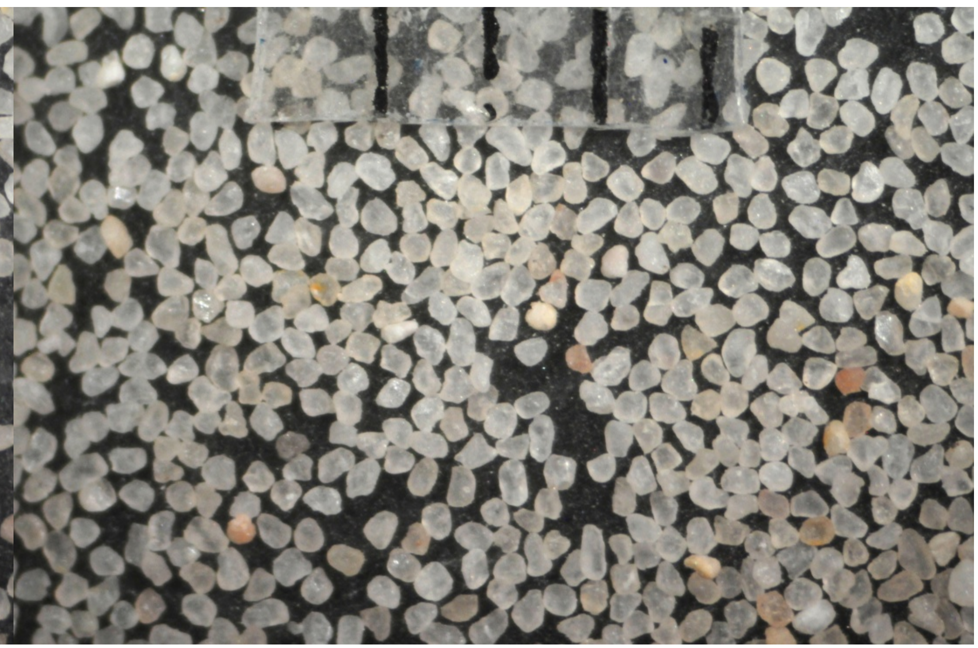

FS-9 No. 140



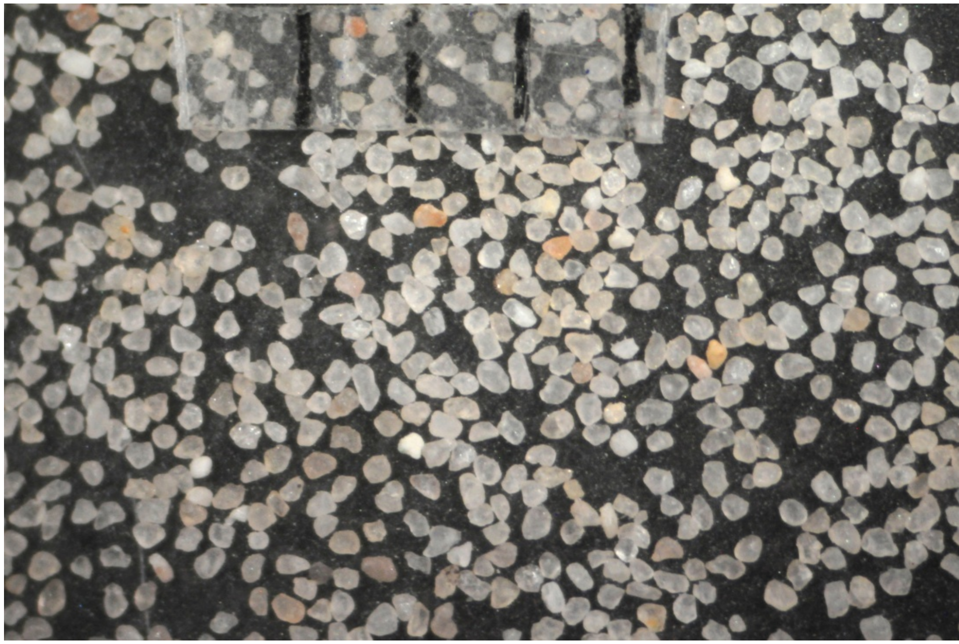
FS-10 No. 40

FS-10 No. 50

FS-10 No. 60



FS-10 No. 70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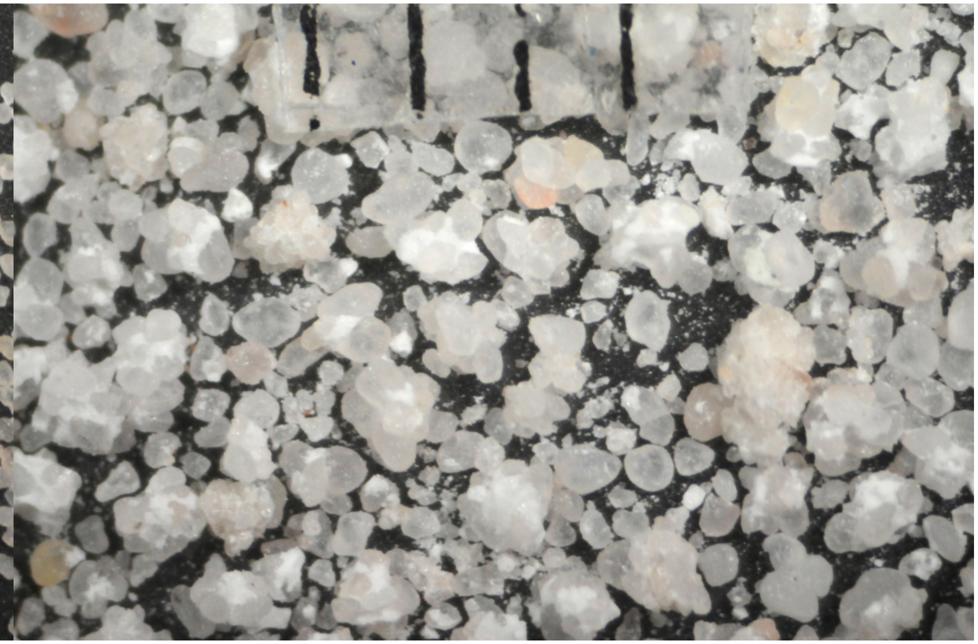
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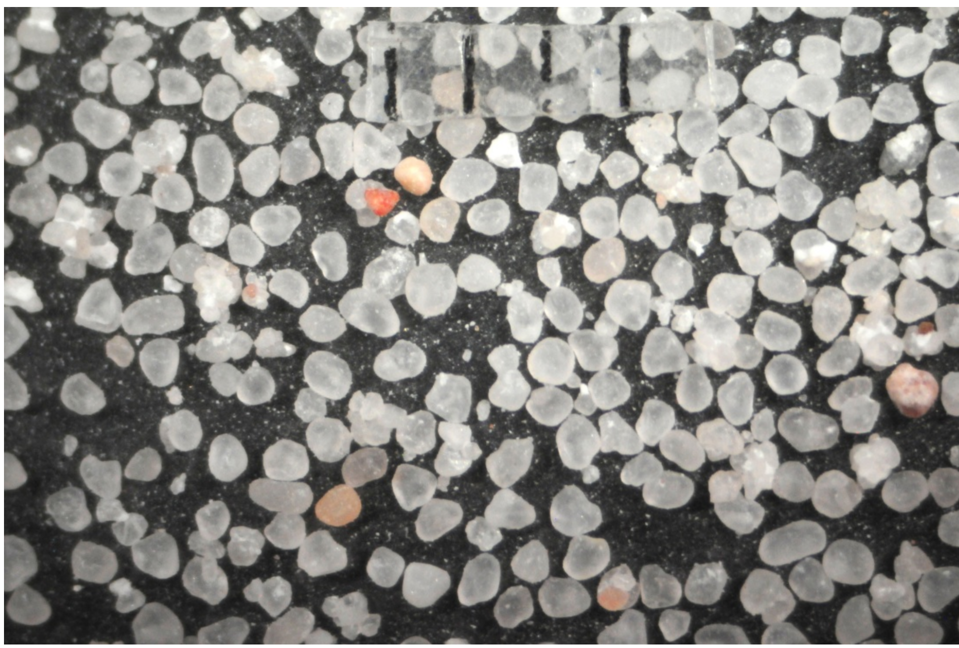
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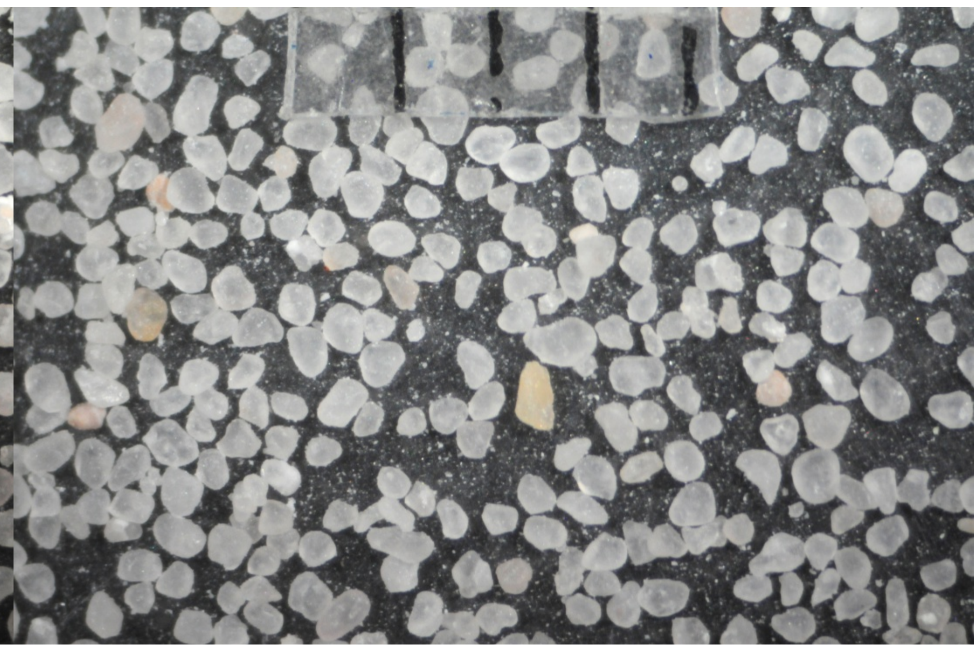
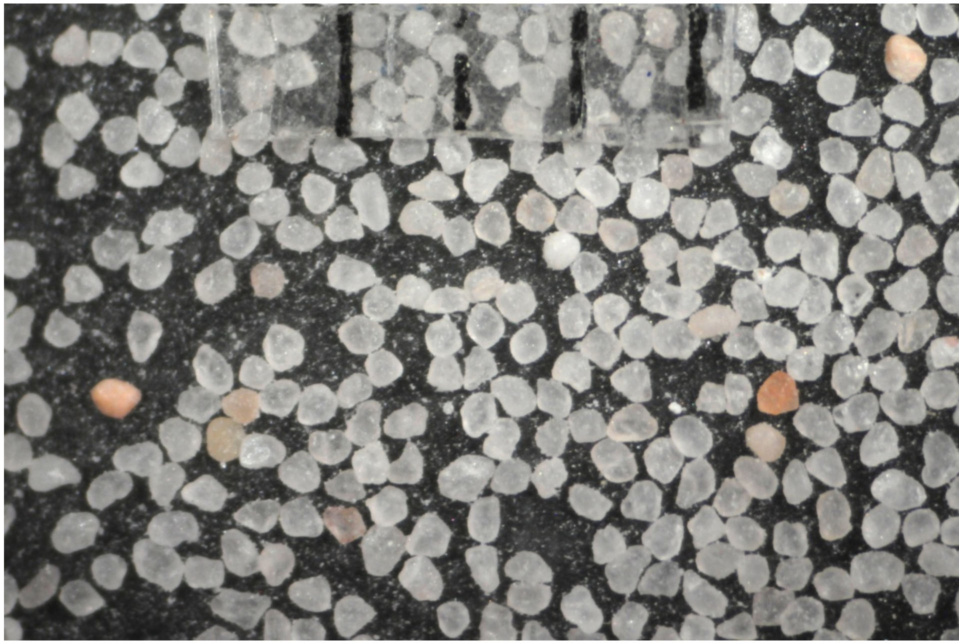
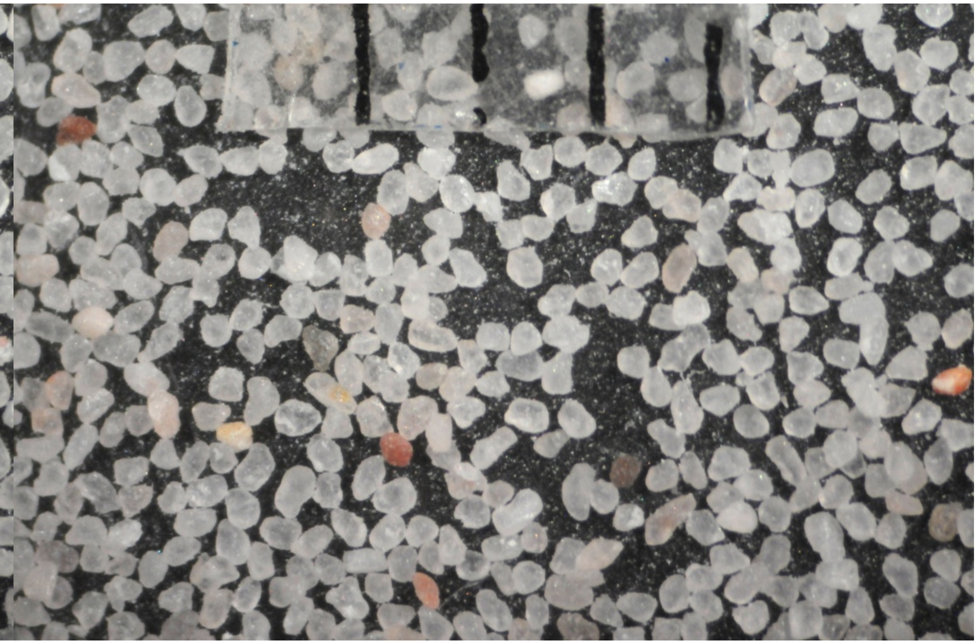

FS-11 No. 50


FS-11 No. 60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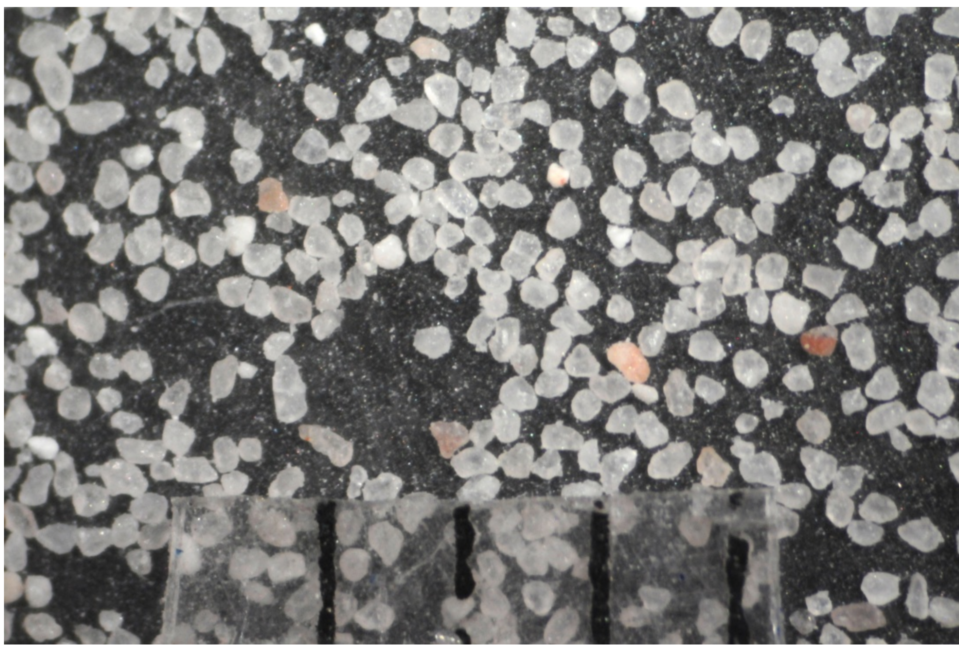
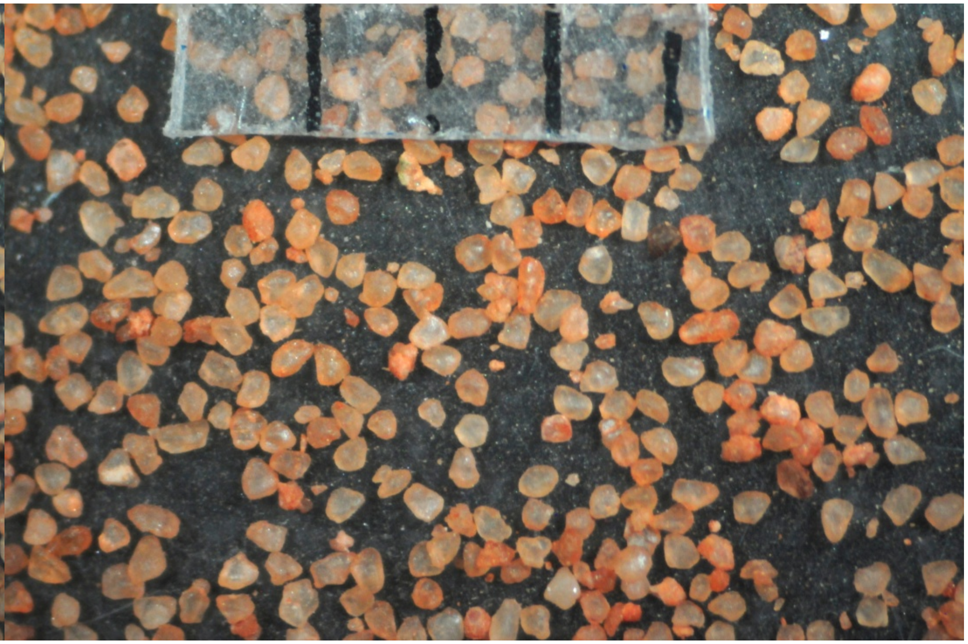

FS-11 No. 140


FS-12 No. 50


FS-12 No. 60


FS-12 No. 70


FS-12 No. 140


FS-13 No. 40

FS-13 No. 50

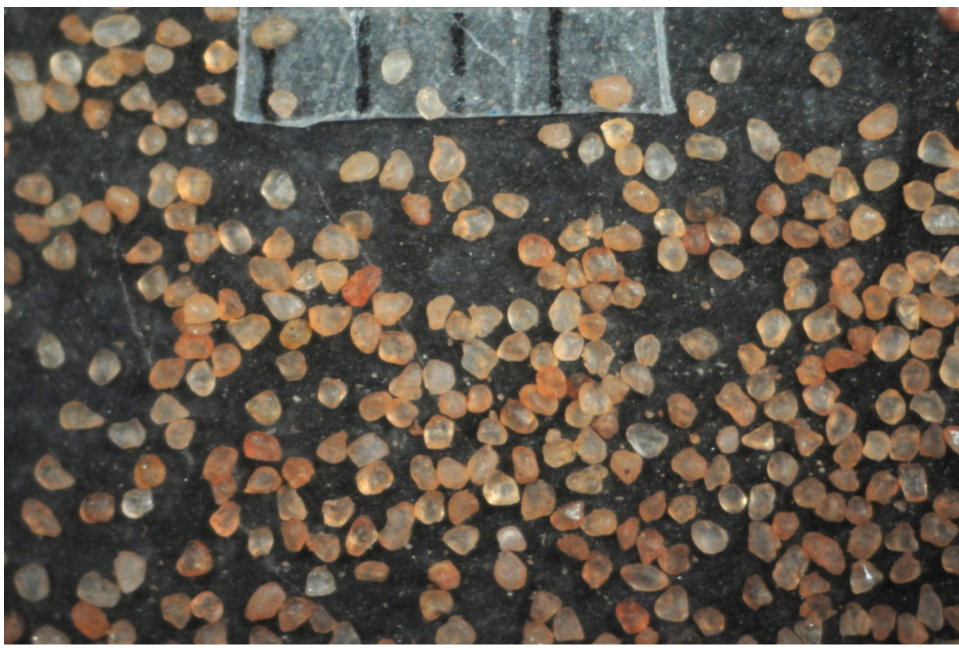
FS-13 No. 60

FS-13 No. 70

FS-13 No. 140

FS-14 No. 40

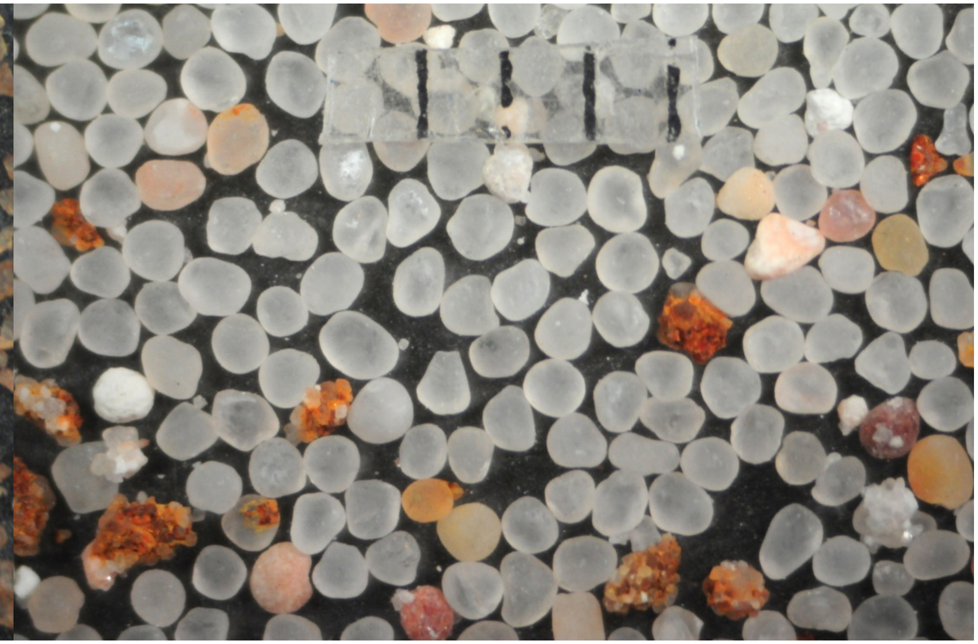
FS-14 No. 50



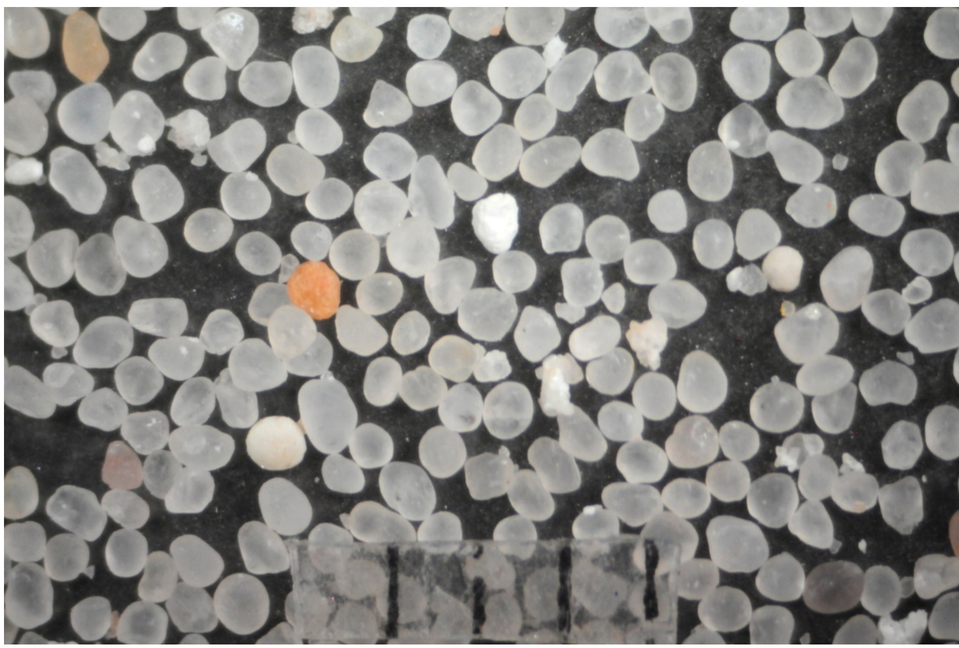
FS-14 No. 60

FS-14 No. 70

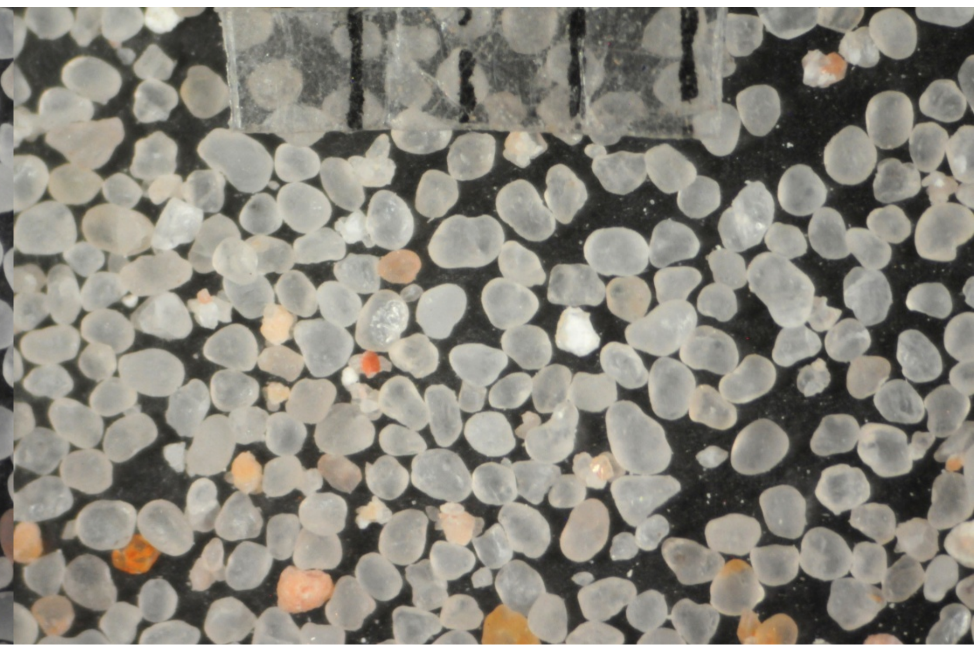
FS-14 No. 140



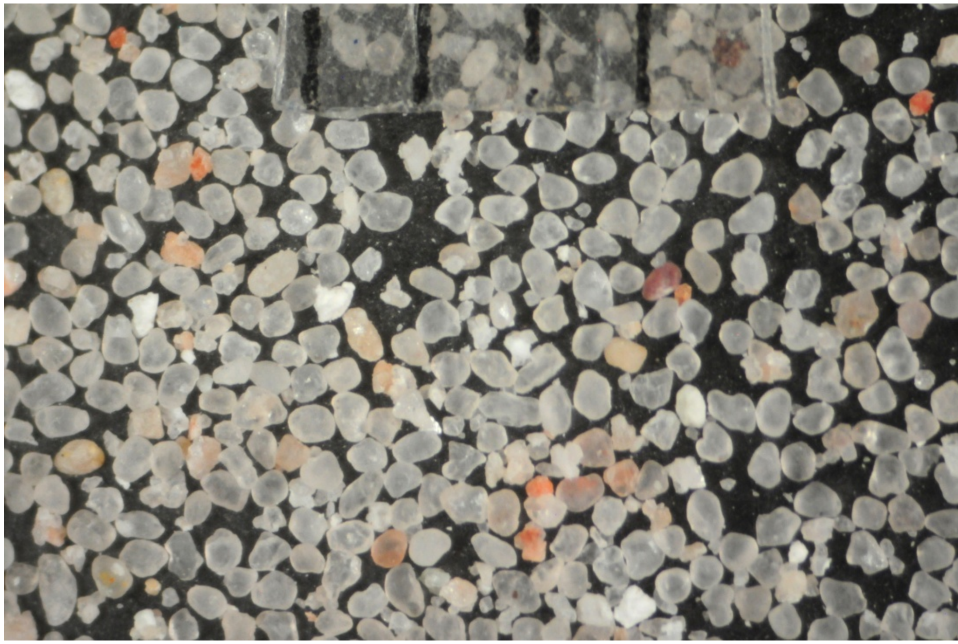
FS-15 No. 30



FS-15 No. 40



FS-15 No. 50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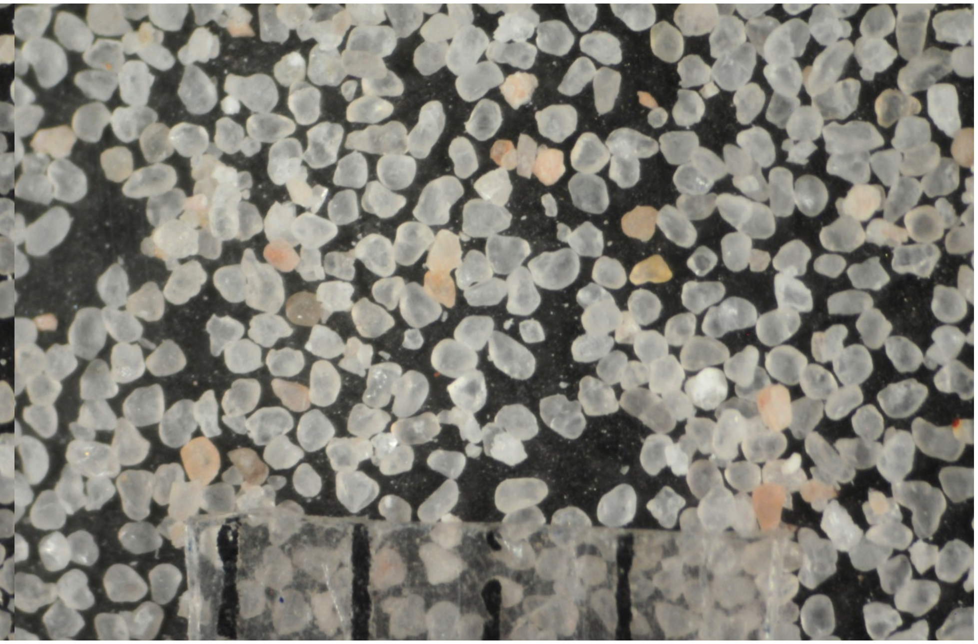
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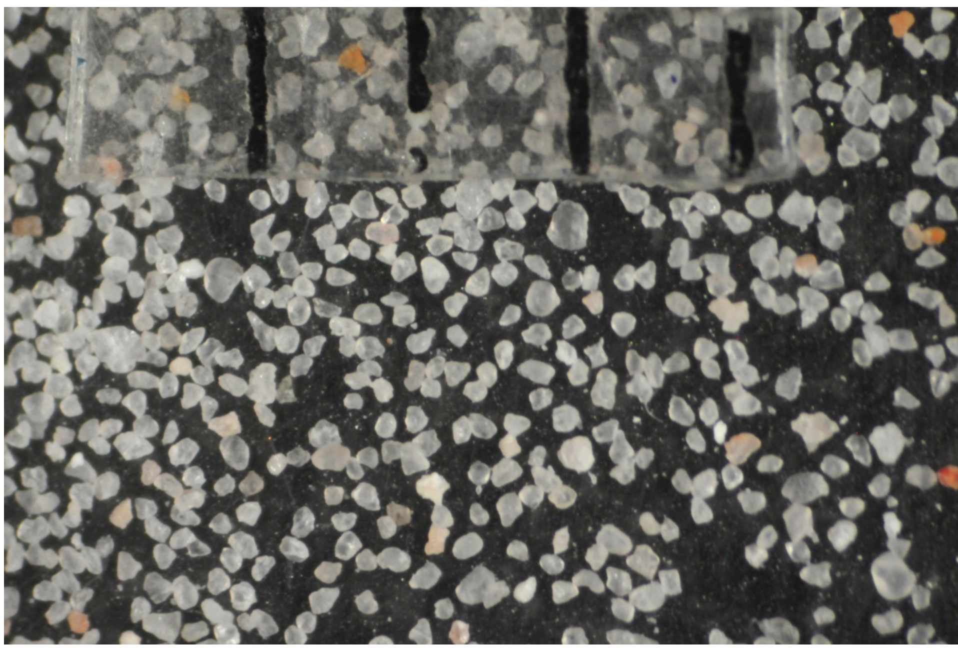
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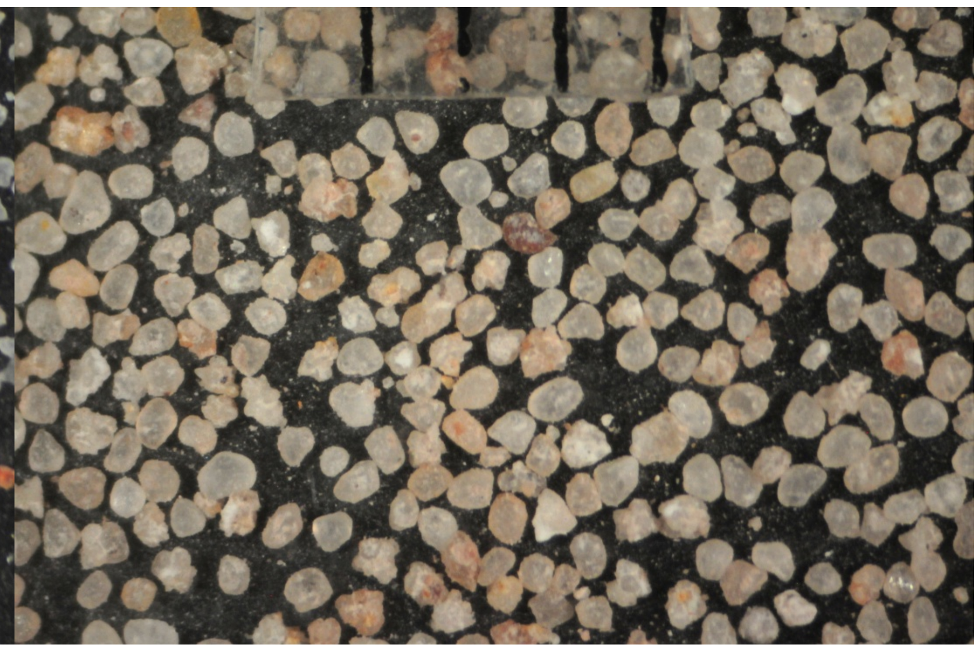
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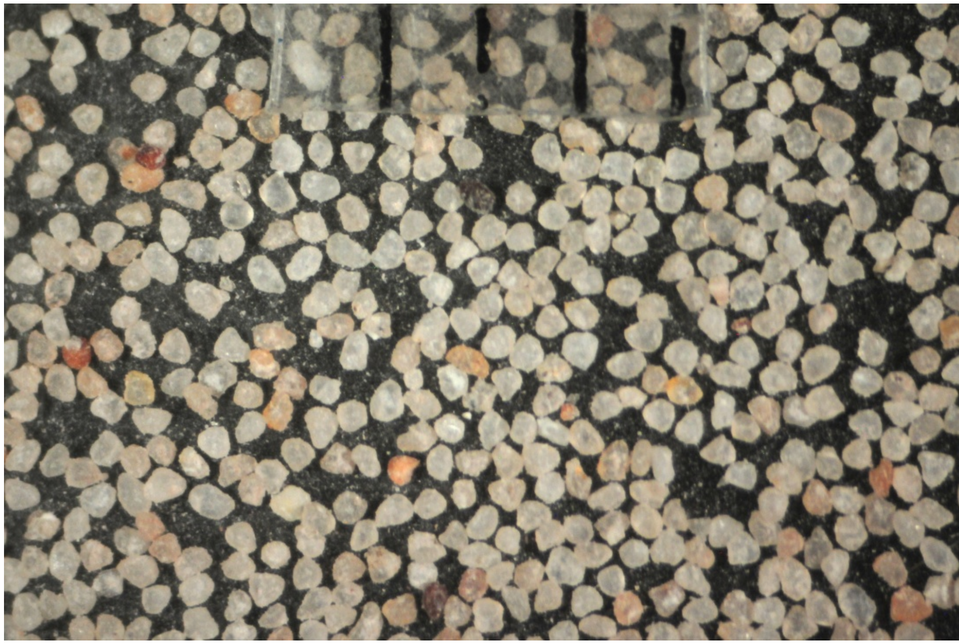
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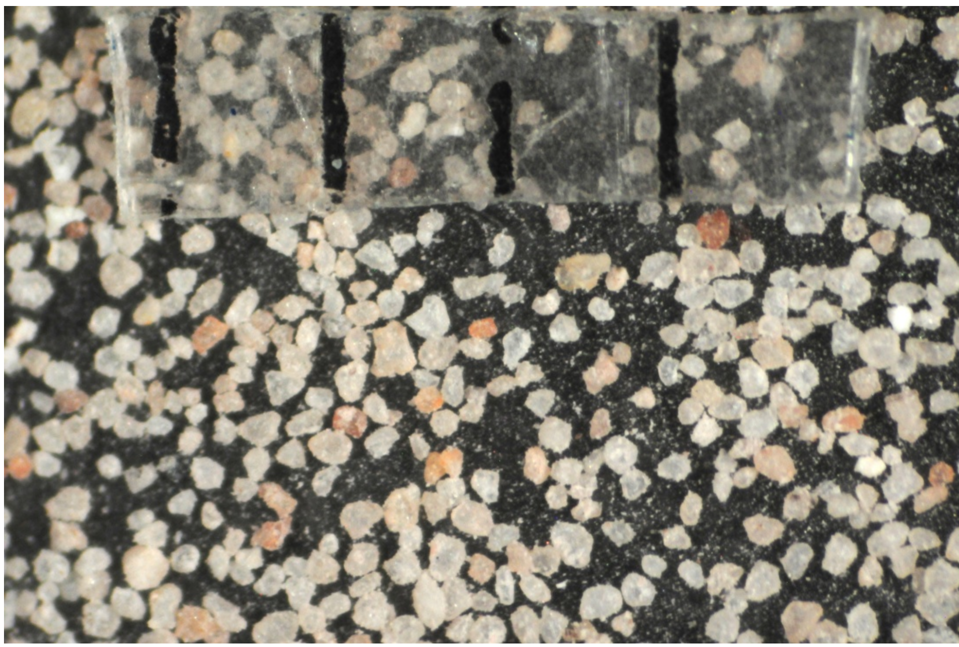
FS-16 No. 70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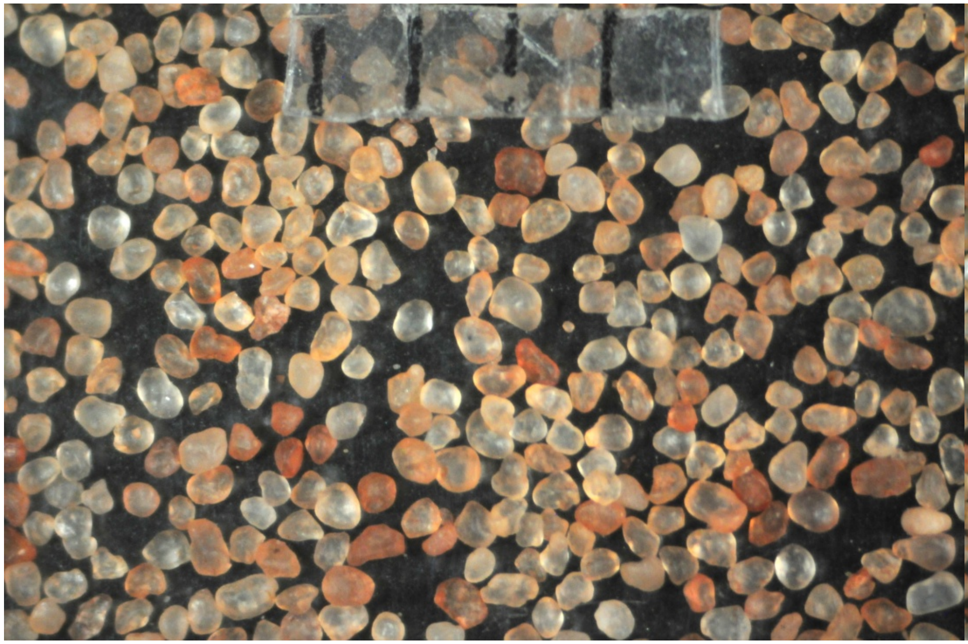
FS-17 No. 40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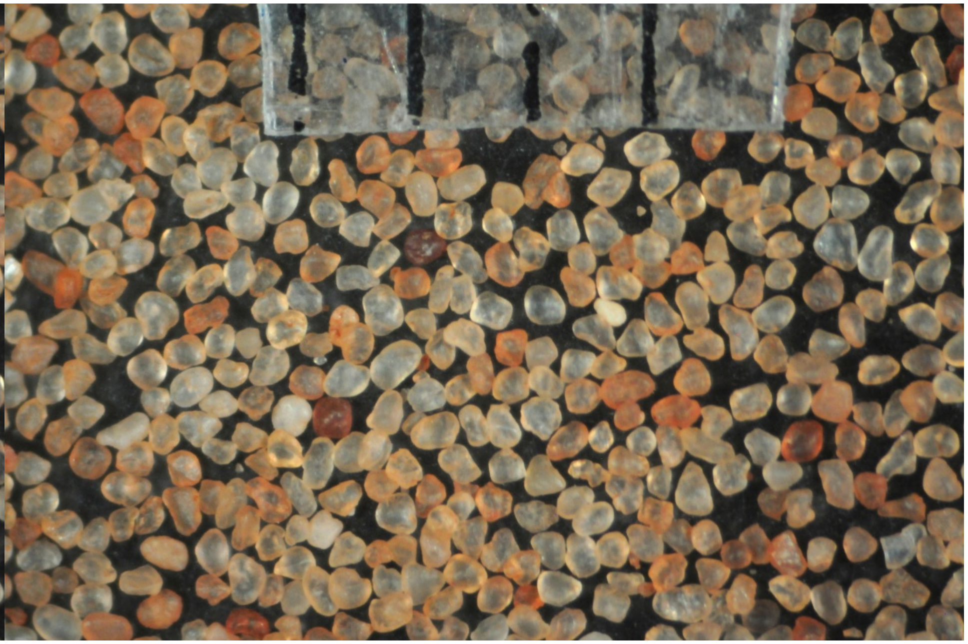
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FS-17 No. 70


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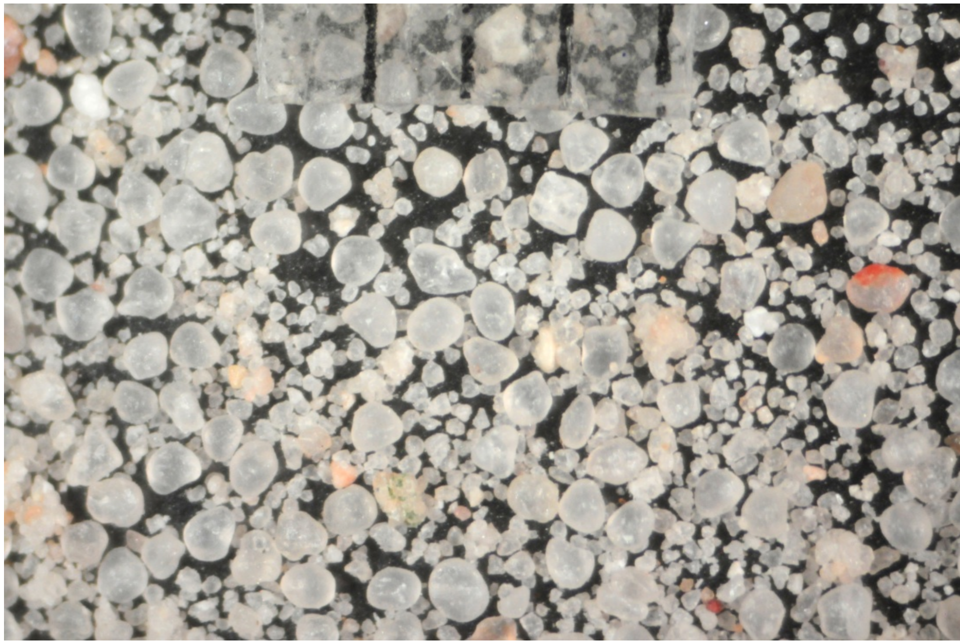
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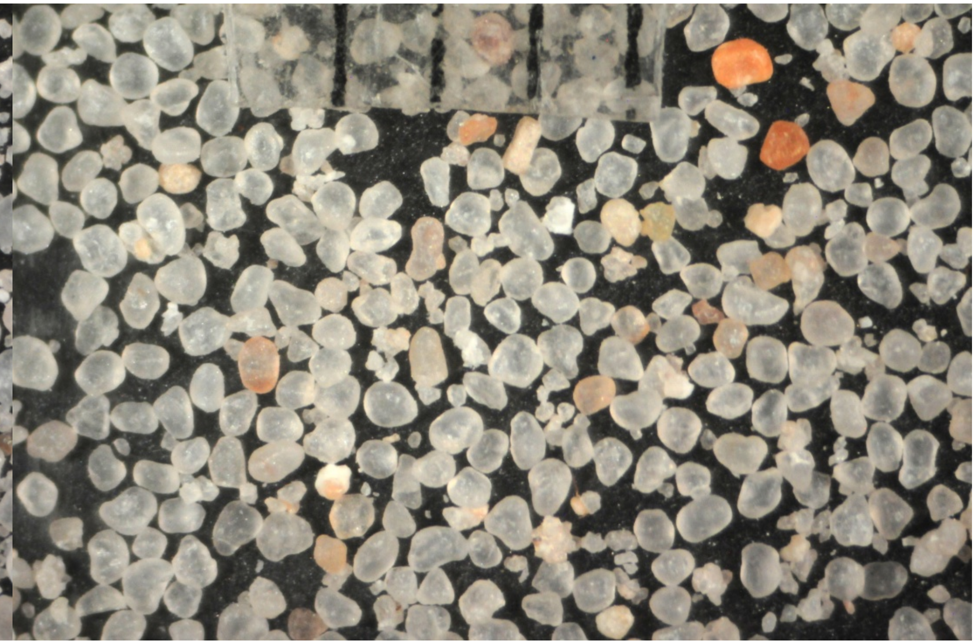
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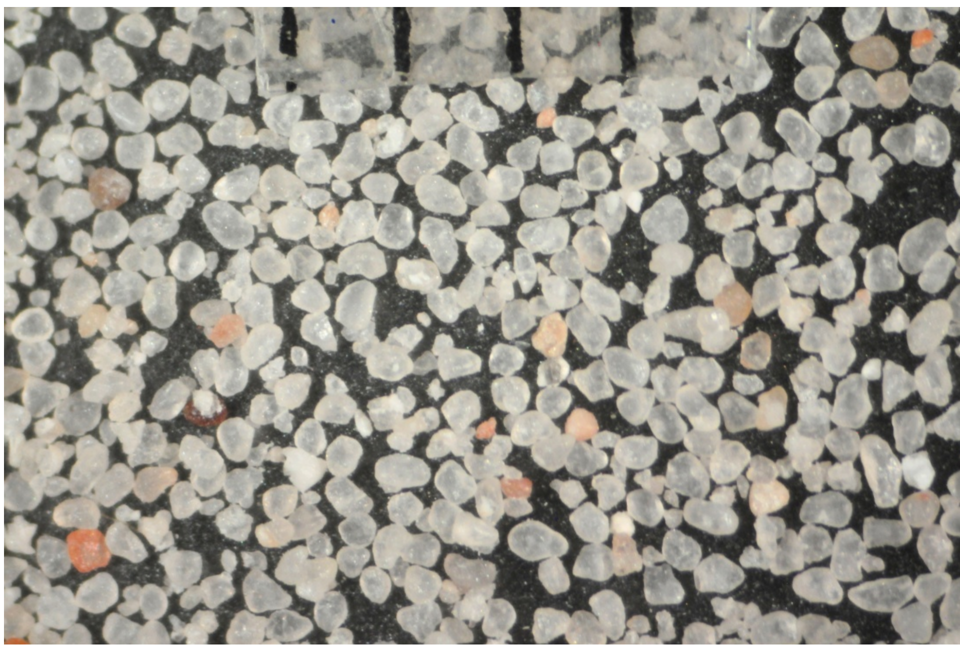
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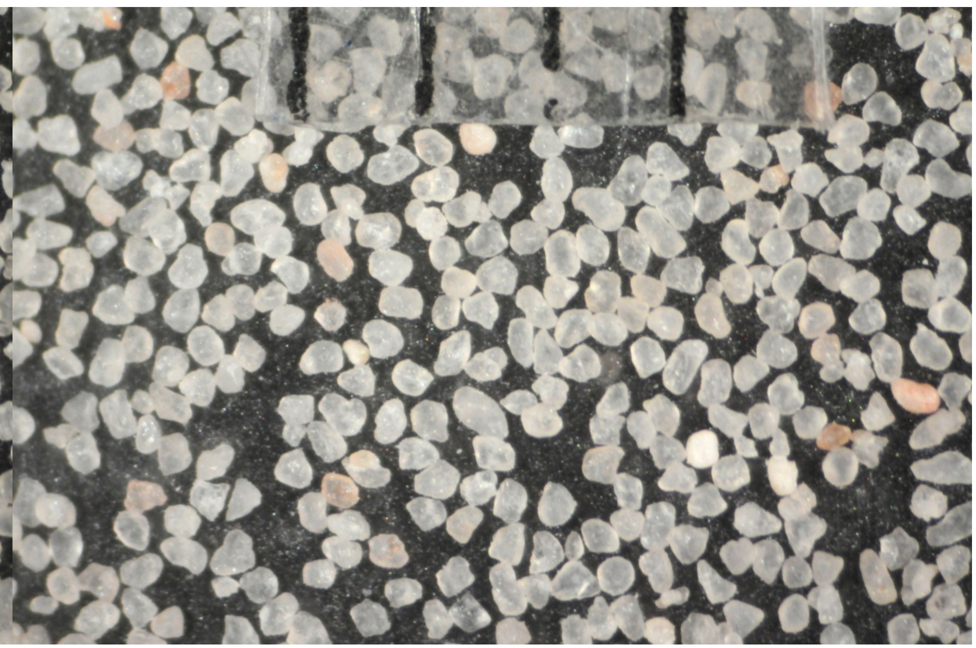
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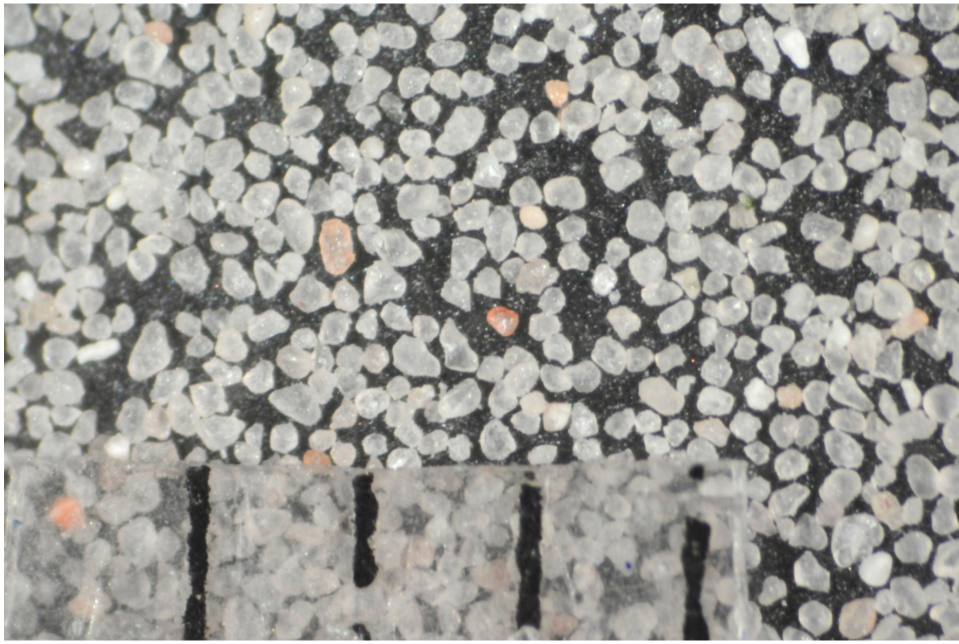

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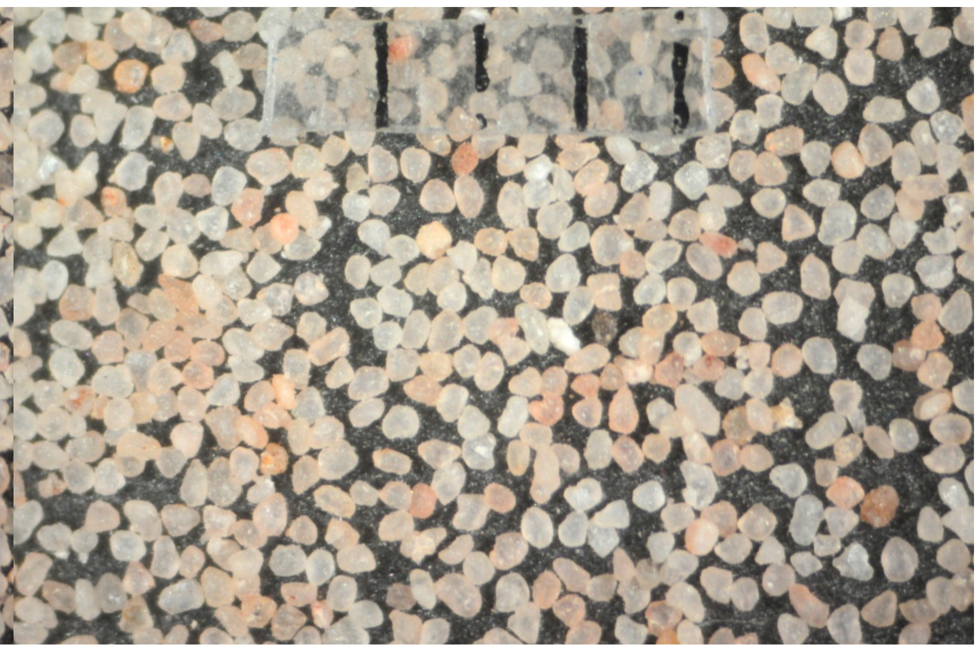
FS-19 No. 40

FS-19 No. 50



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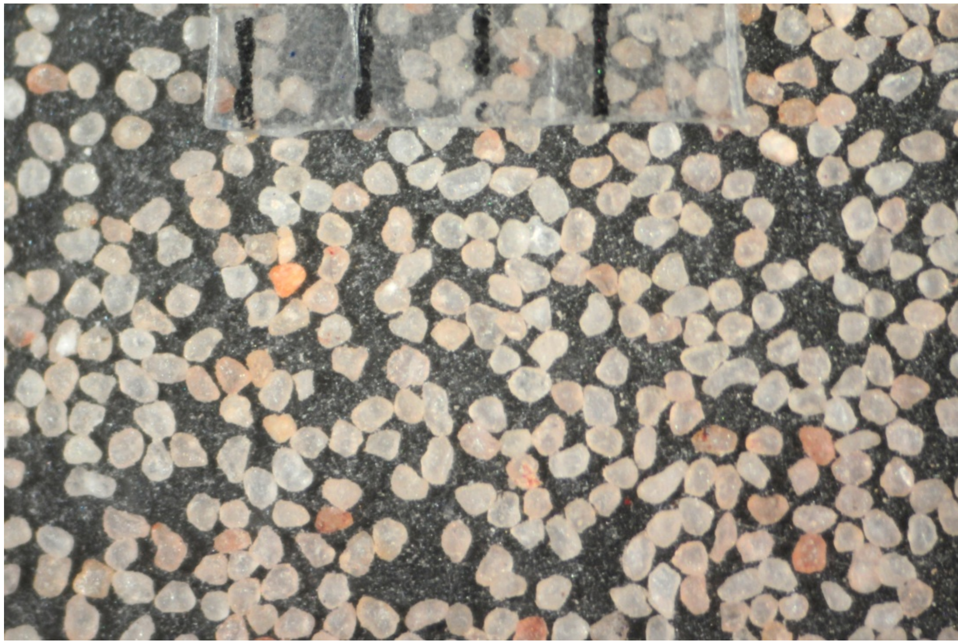

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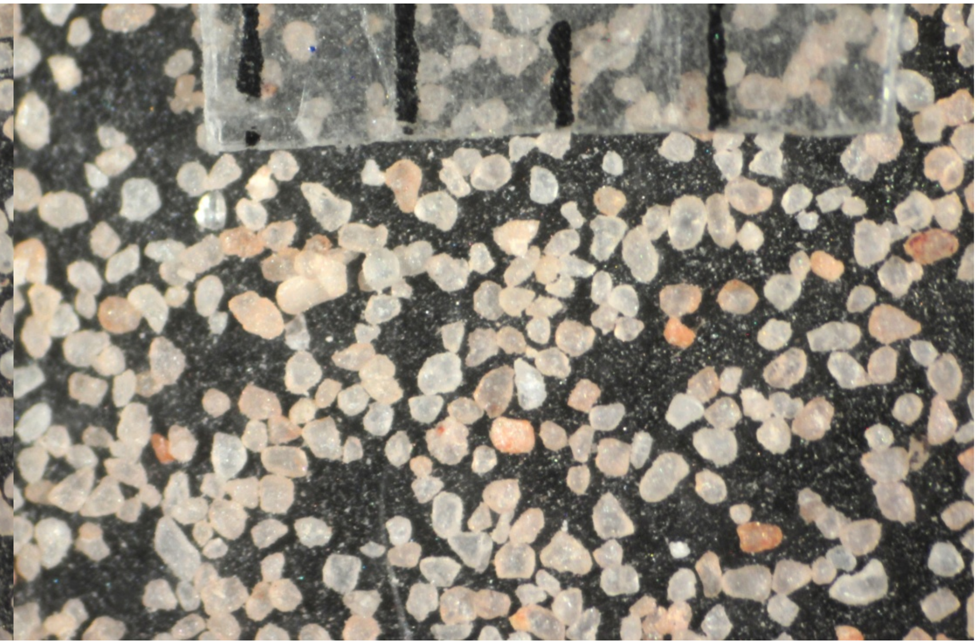

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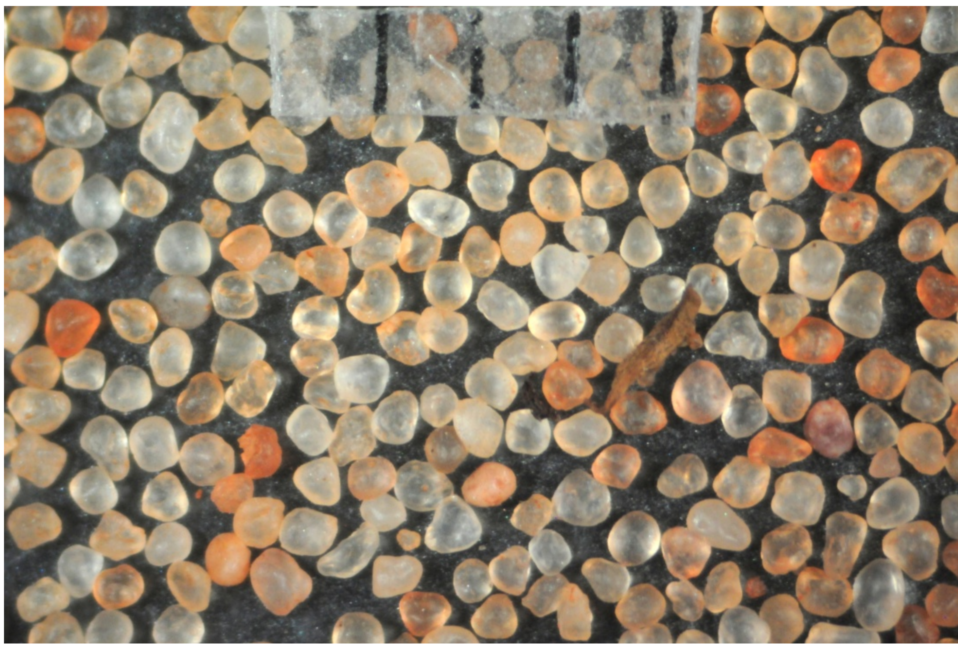

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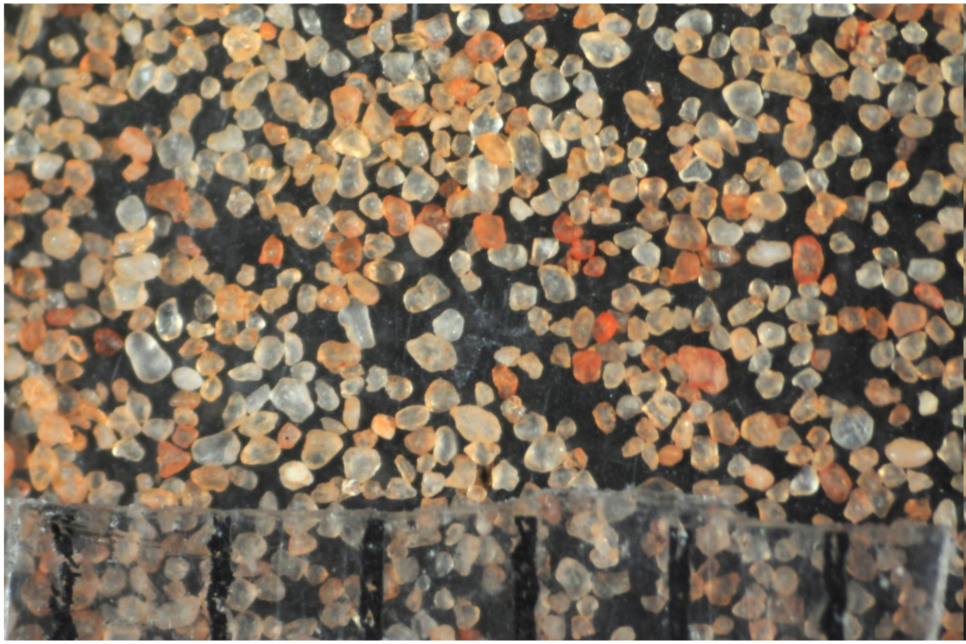
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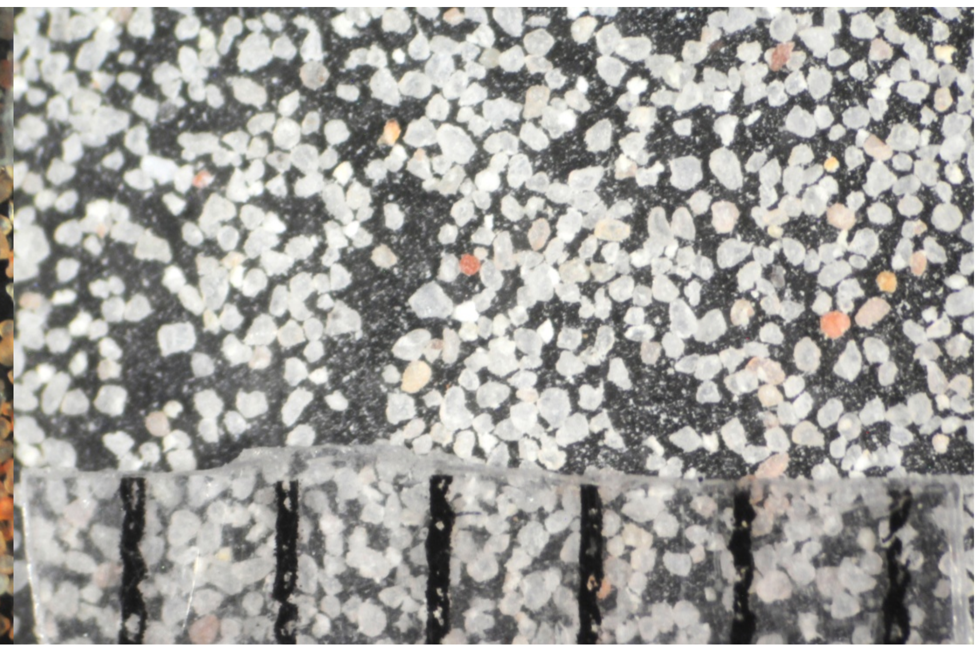

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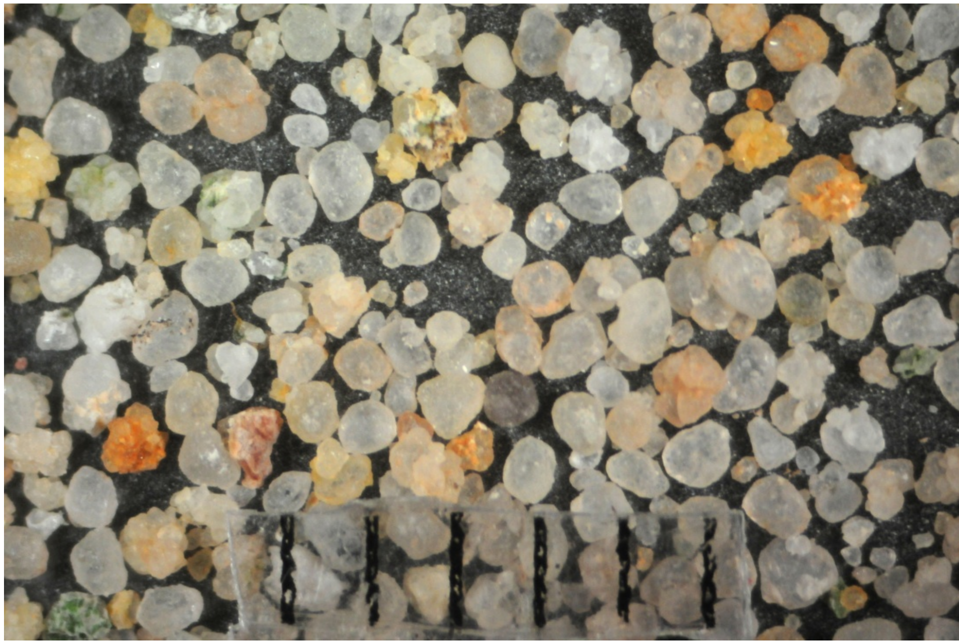
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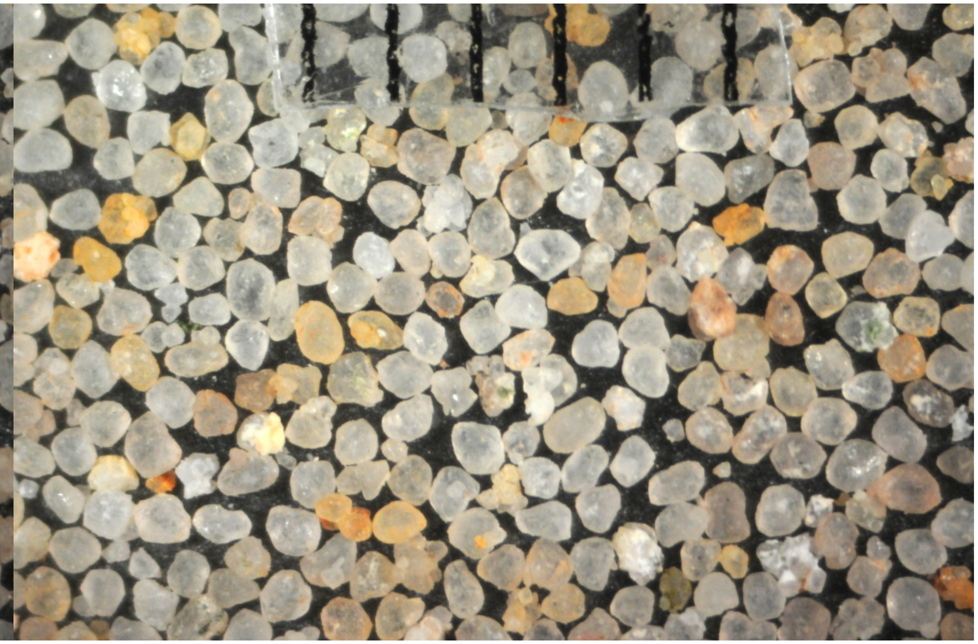
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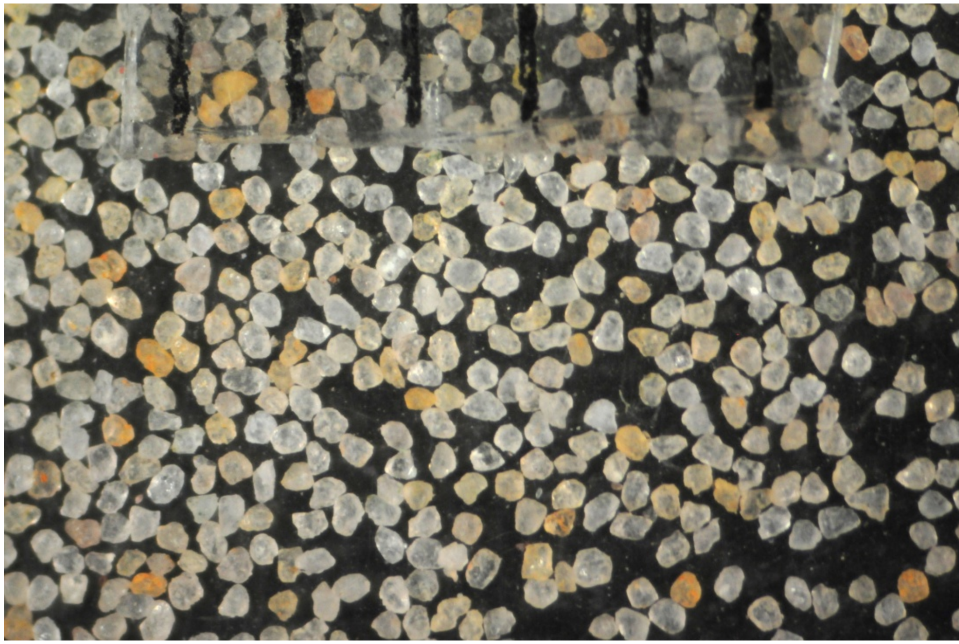
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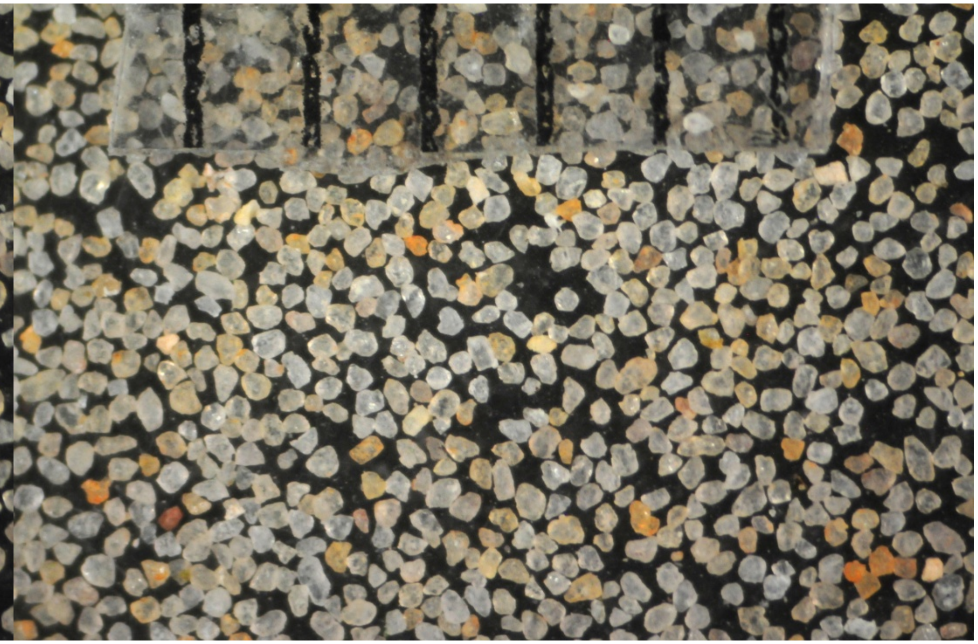
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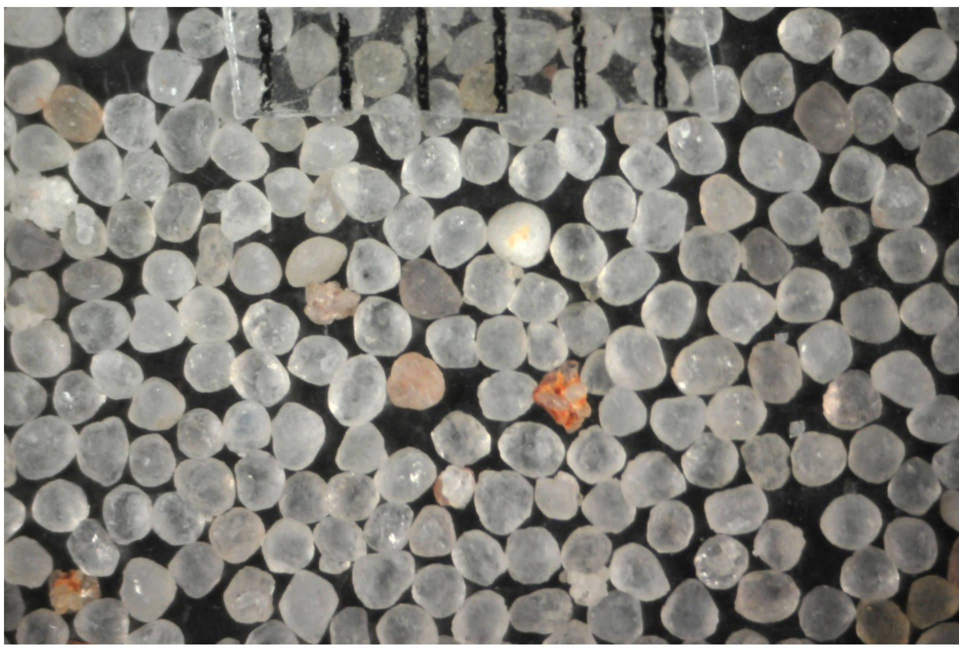
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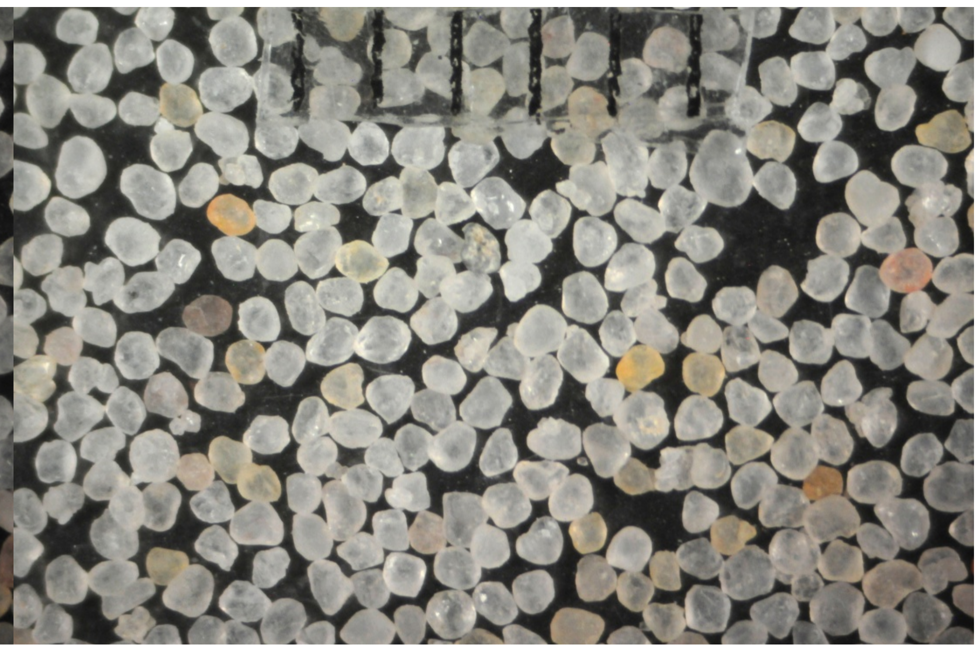
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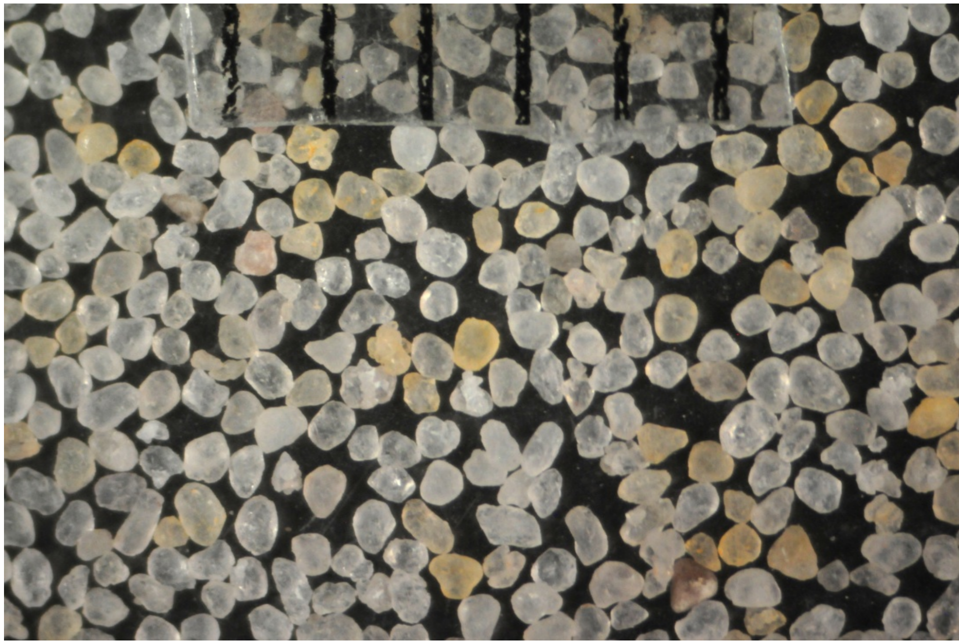

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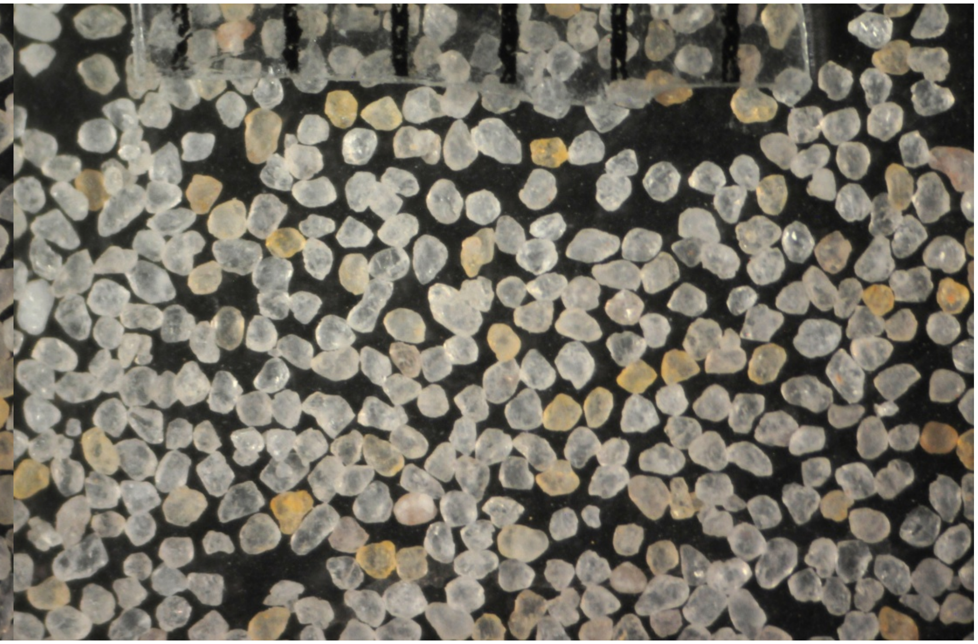

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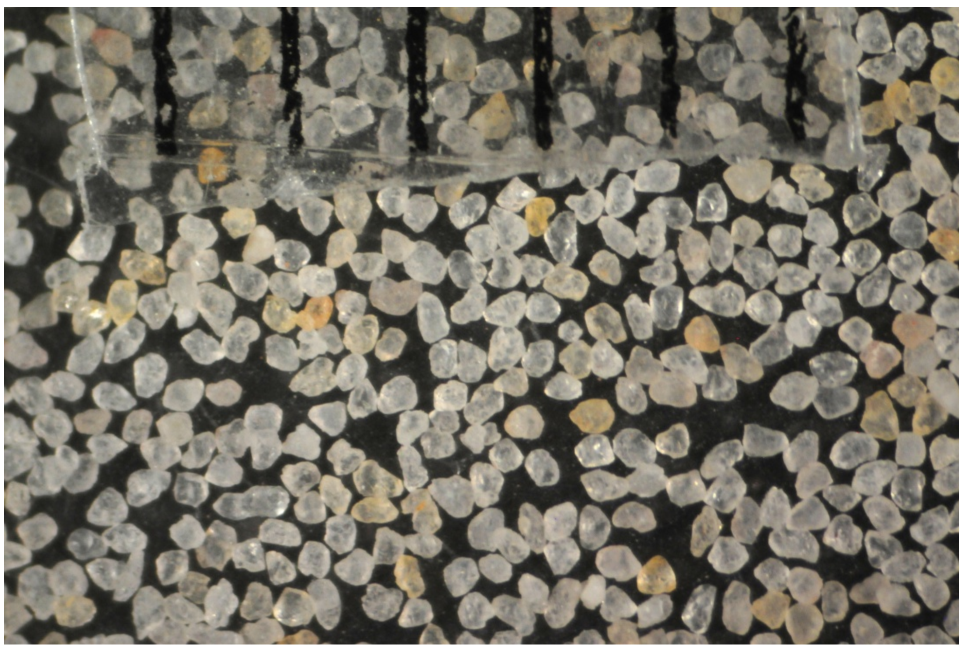

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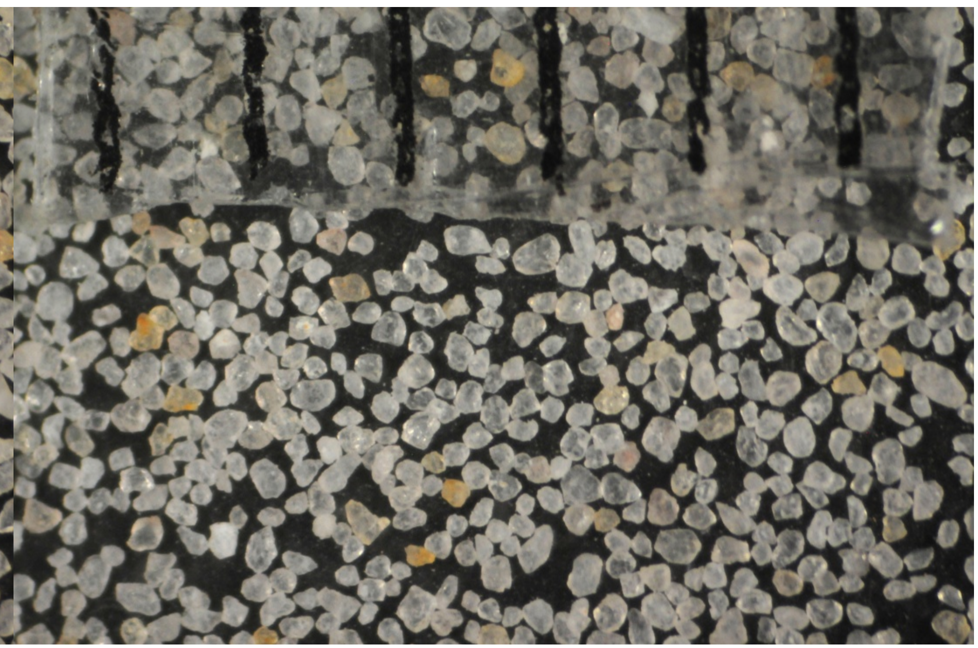

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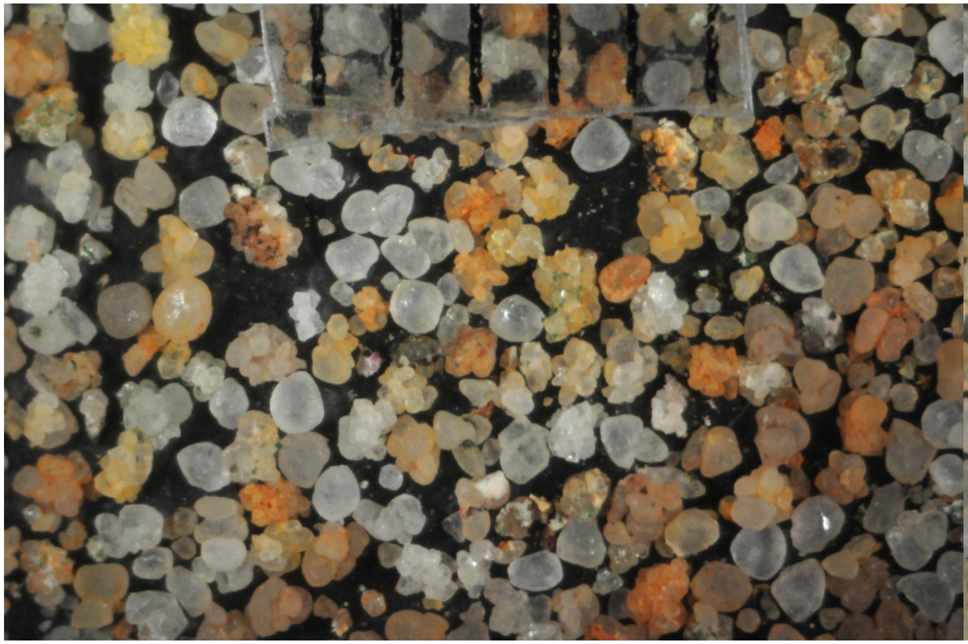
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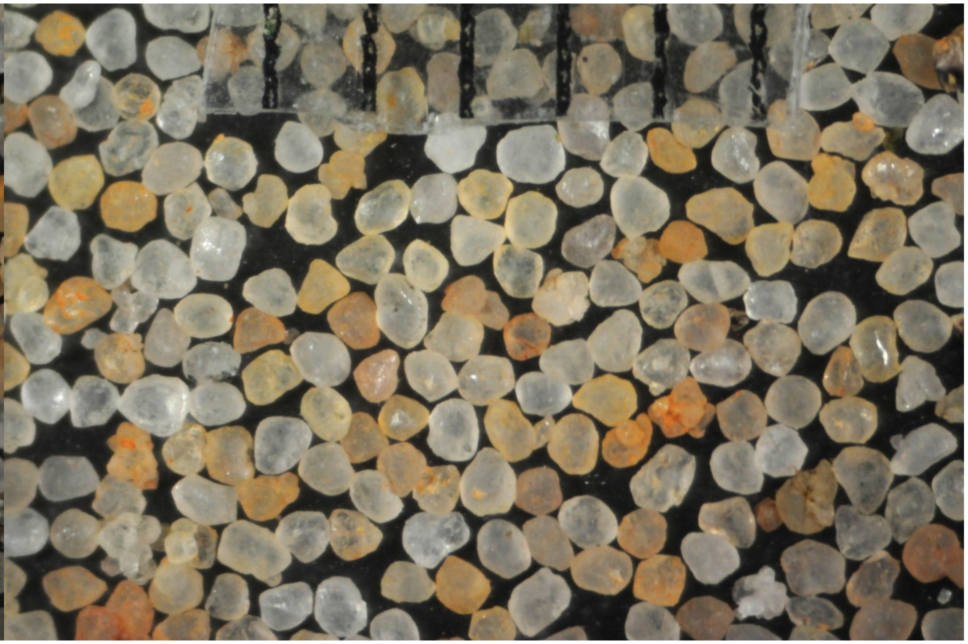
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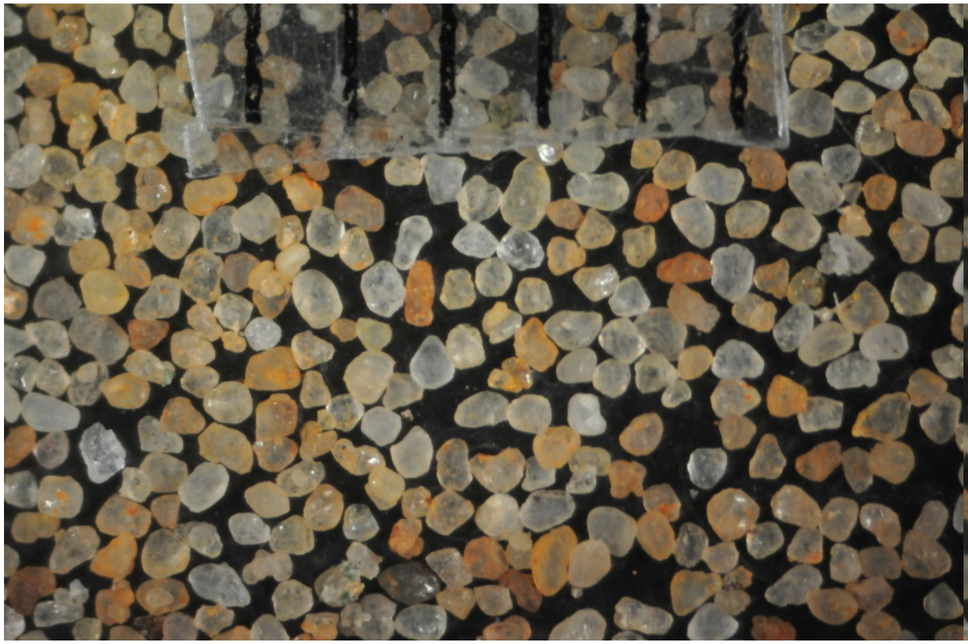
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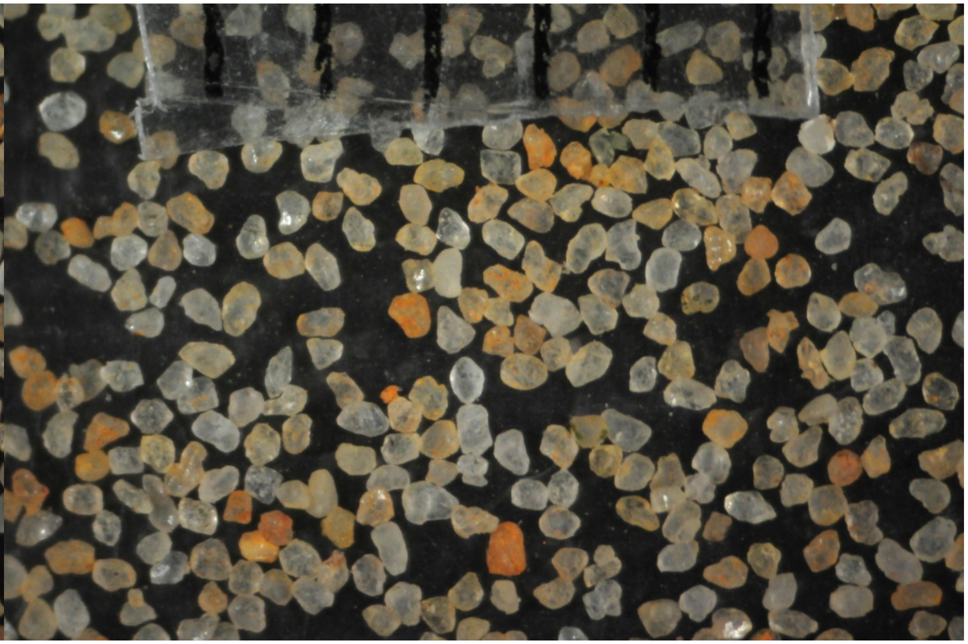
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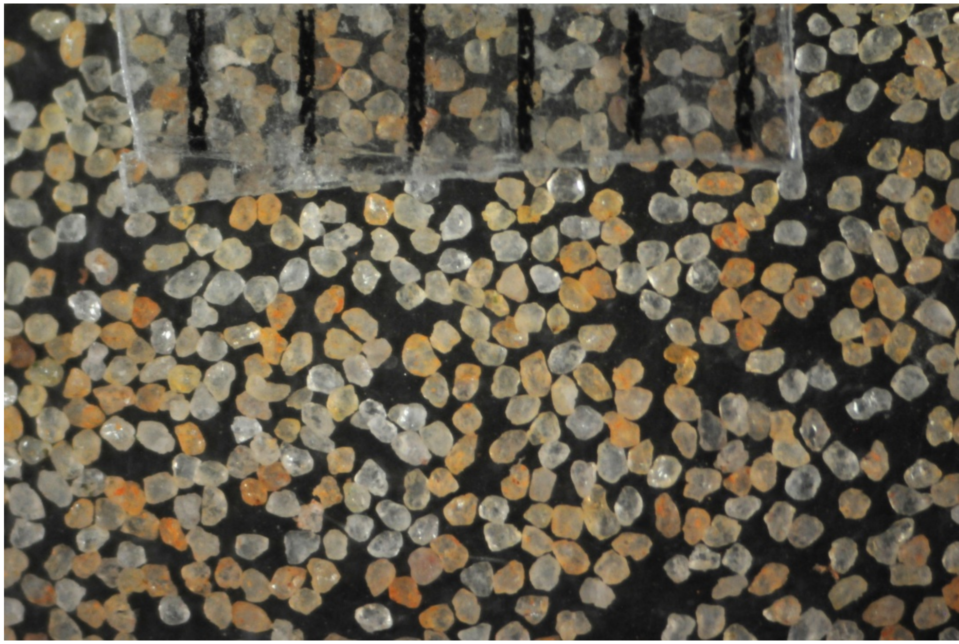
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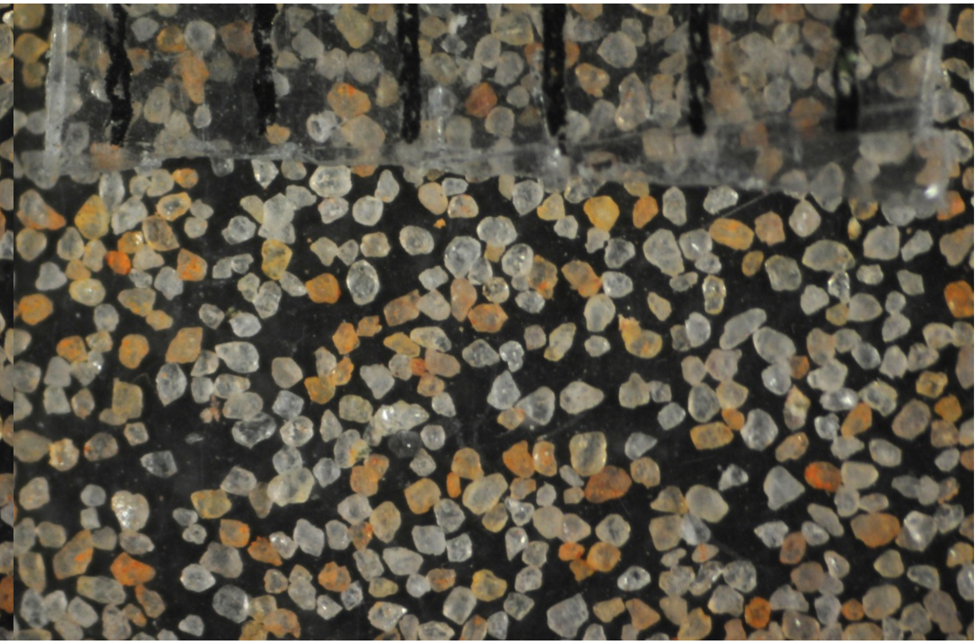
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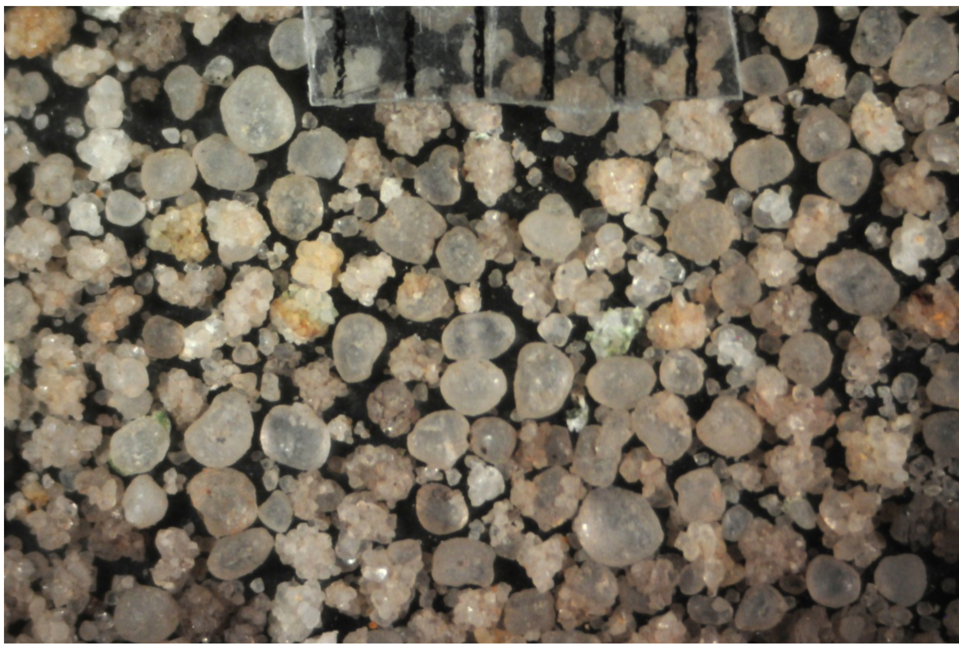
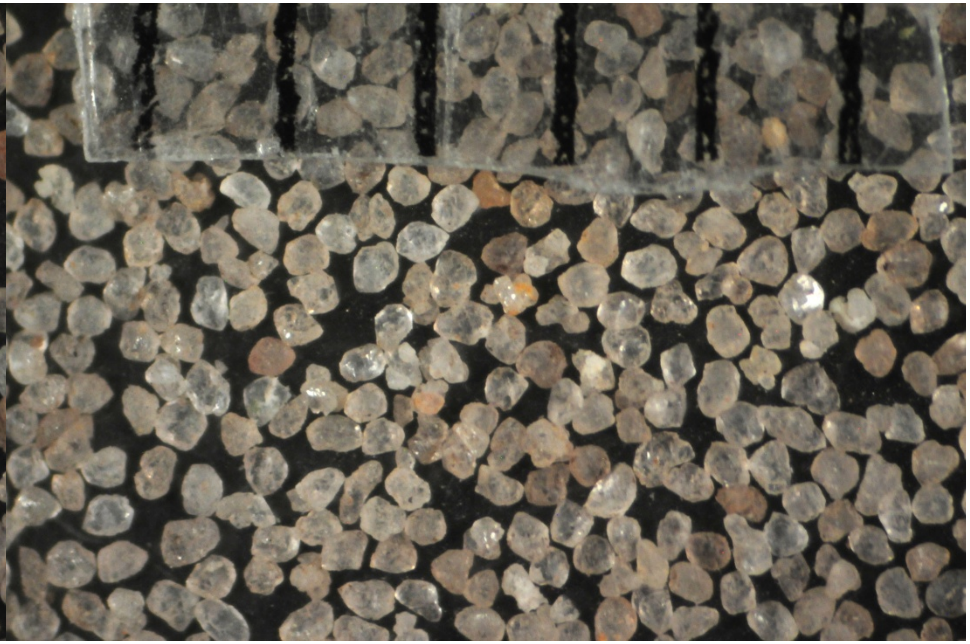

FS-26 No. 30


FS-26 No. 40


FS-26 No. 50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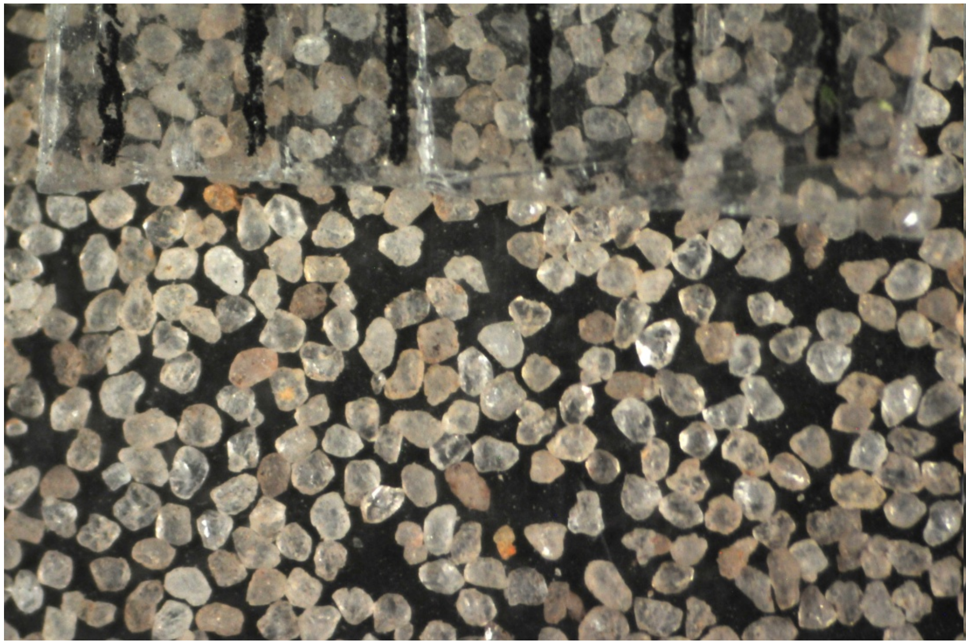
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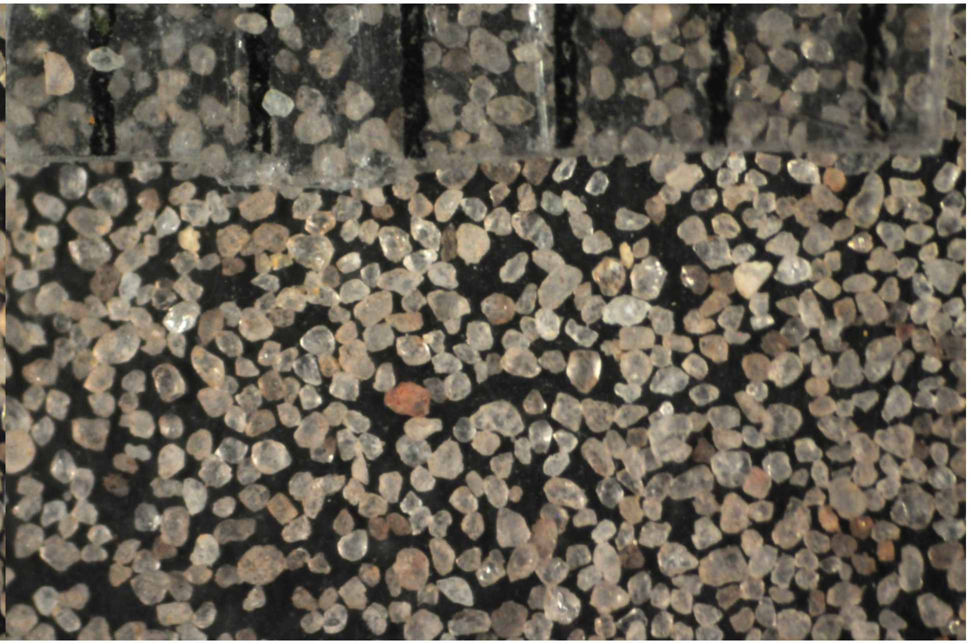
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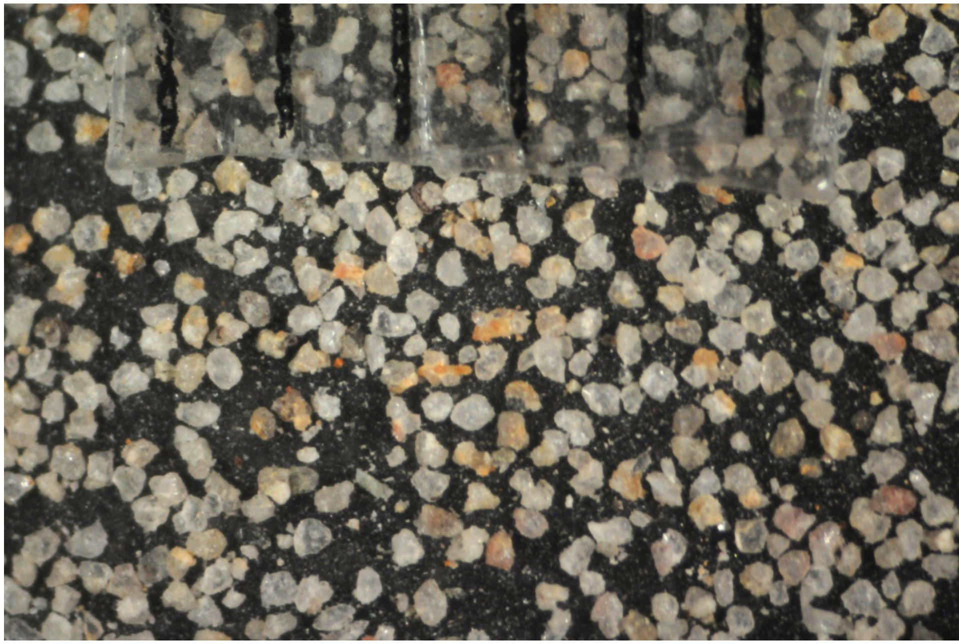
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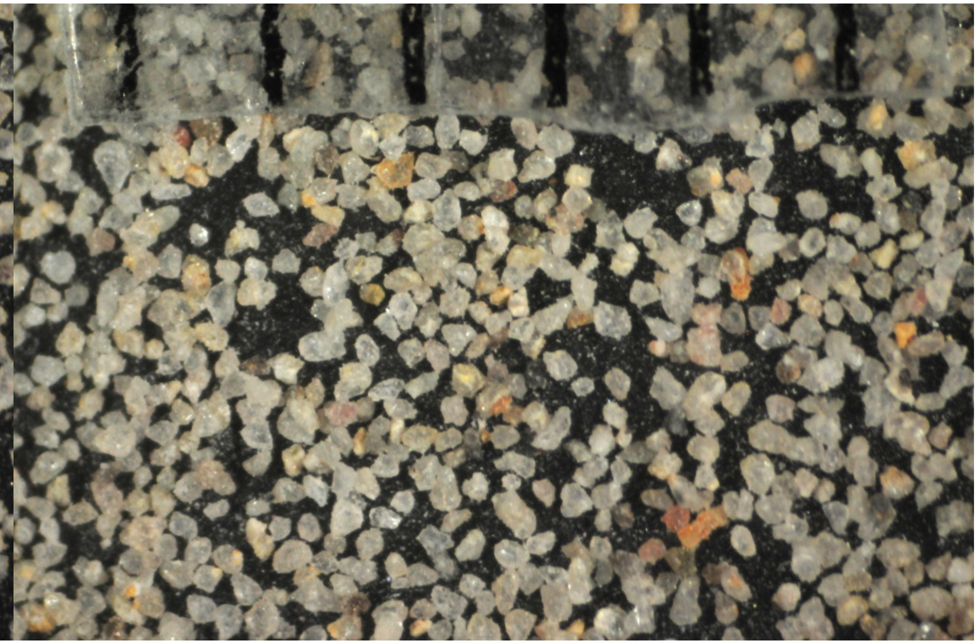
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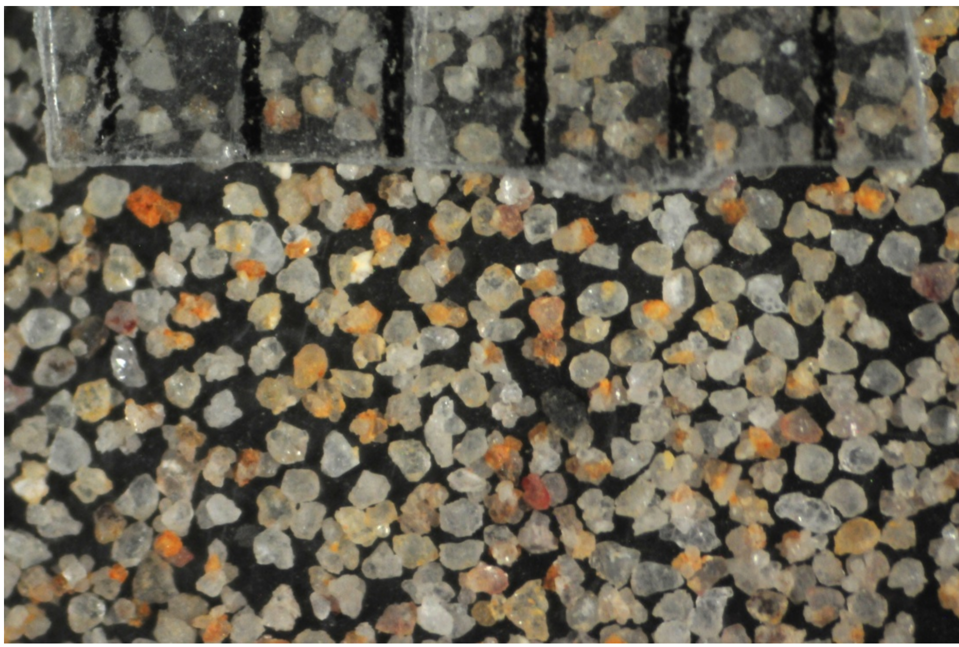
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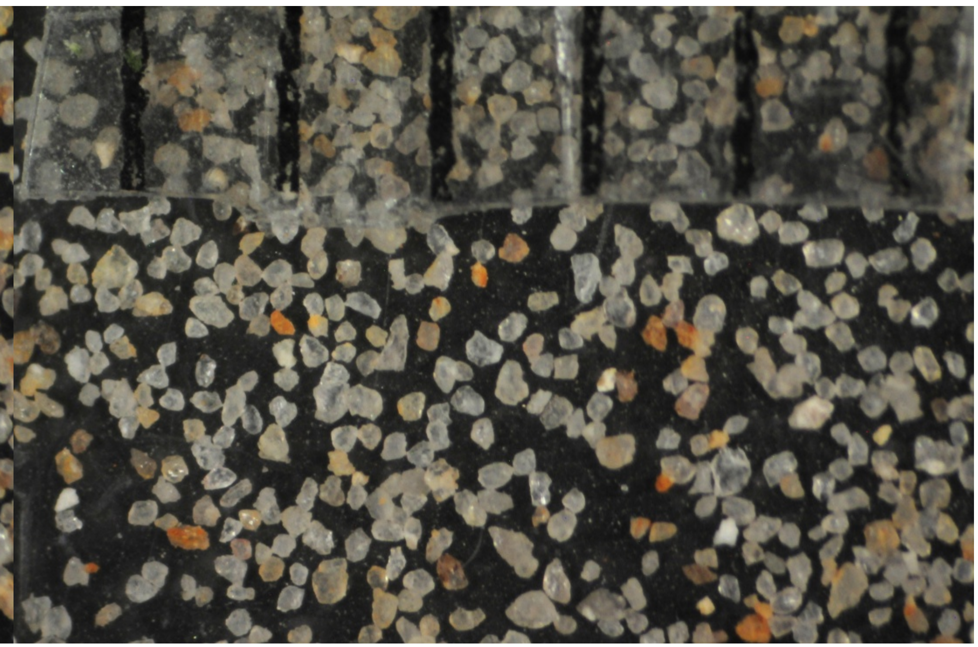
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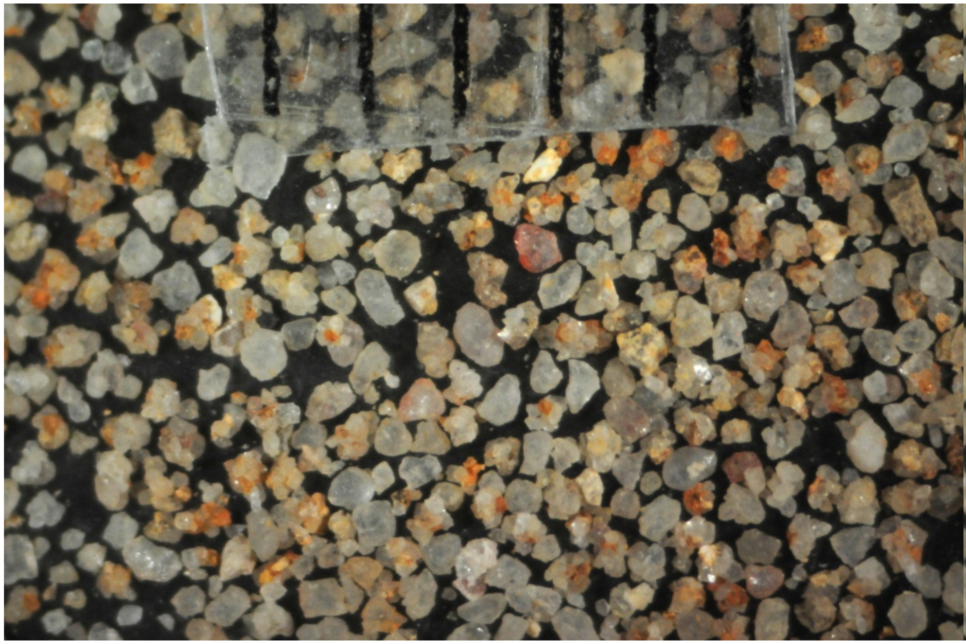
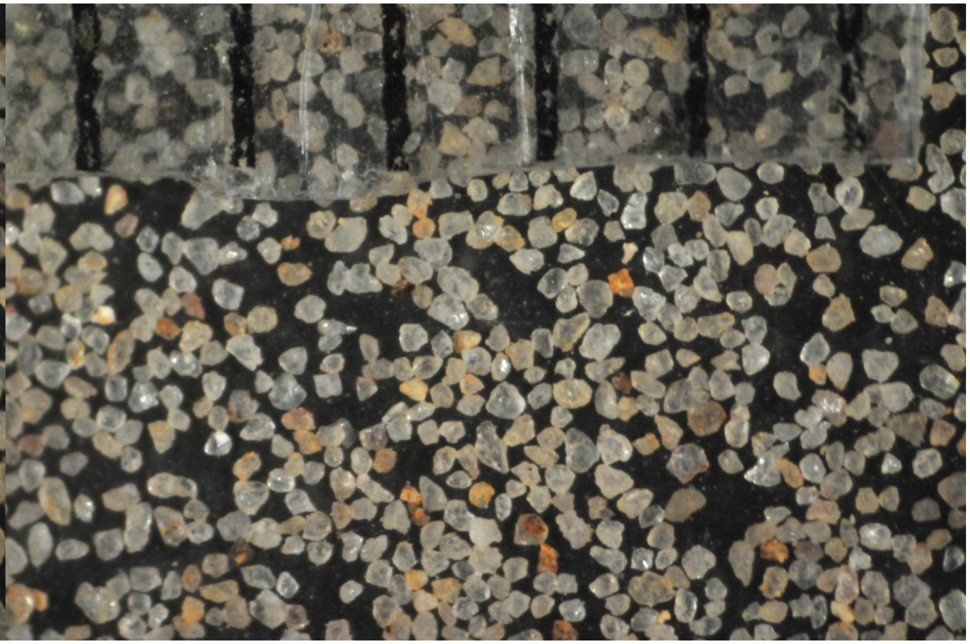


FS-29 No. 50

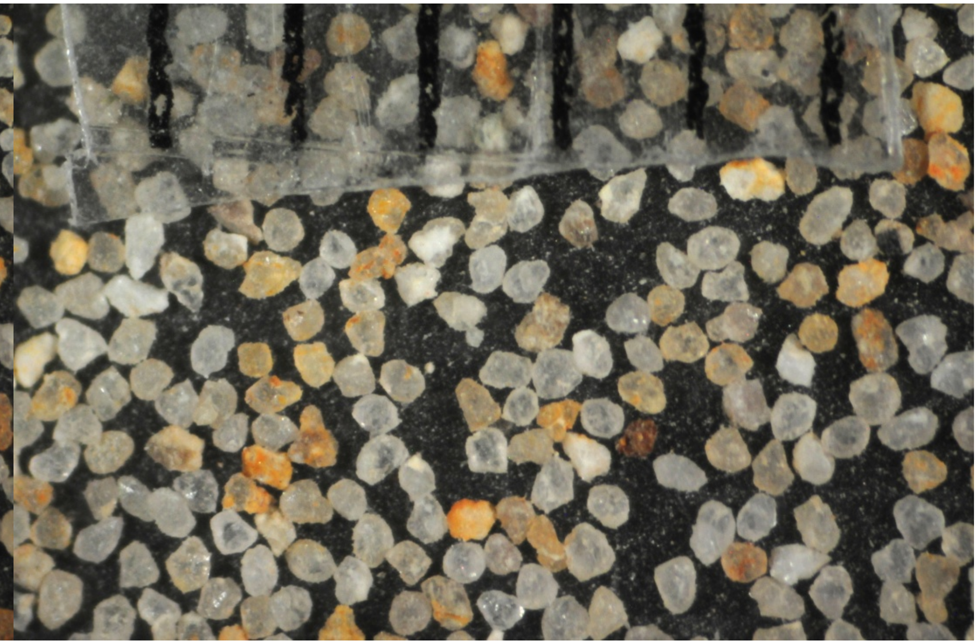
FS-29 No. 60

FS-29 No. 70



FS-29 No. 140


FS-30 No. 50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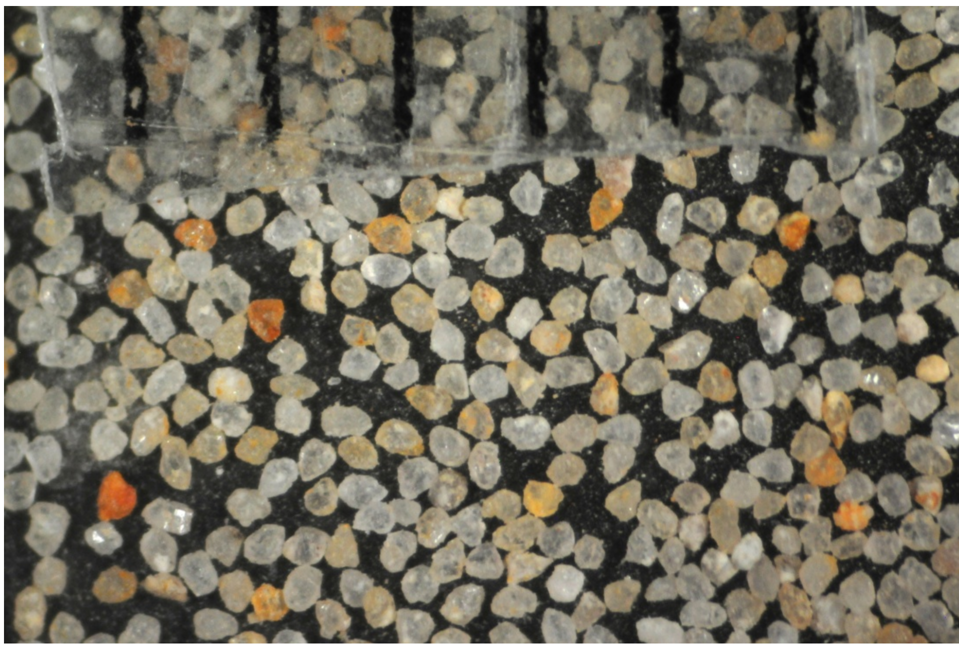
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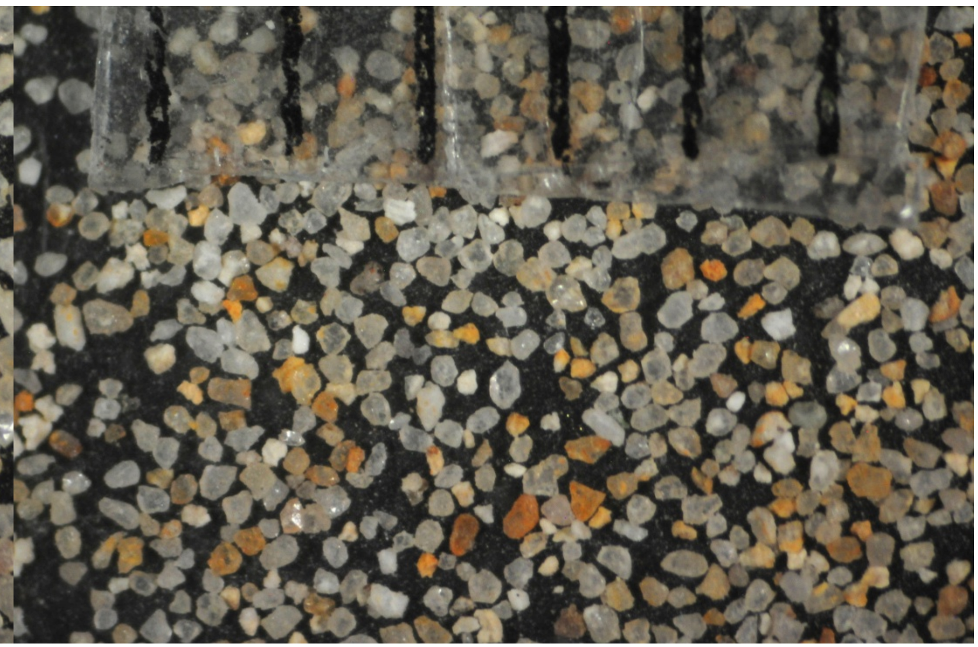
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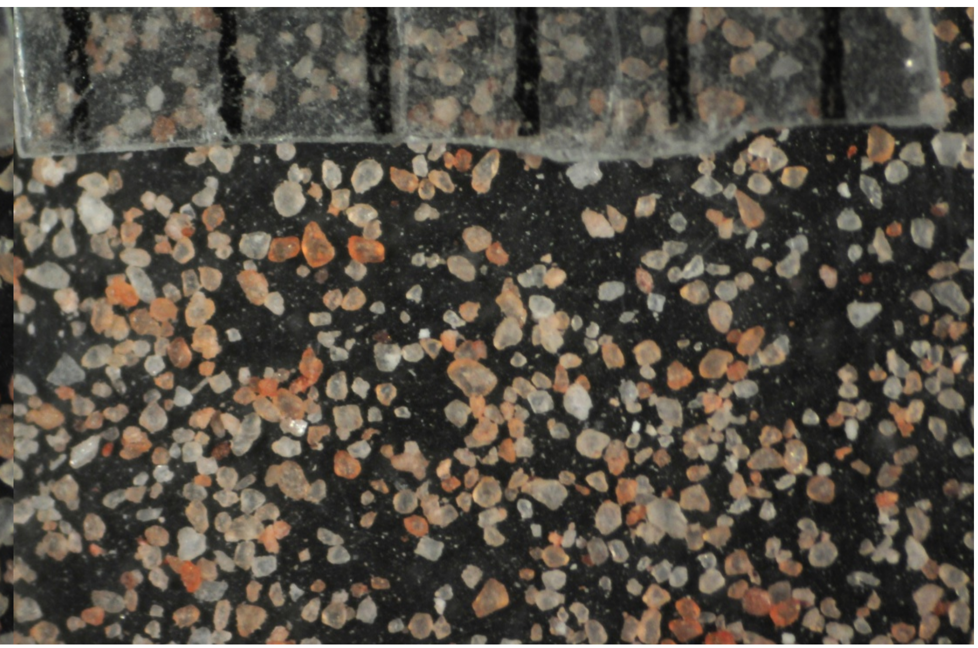
FS-31 No. 140


FS-32 No. 60


FS-32 No. 70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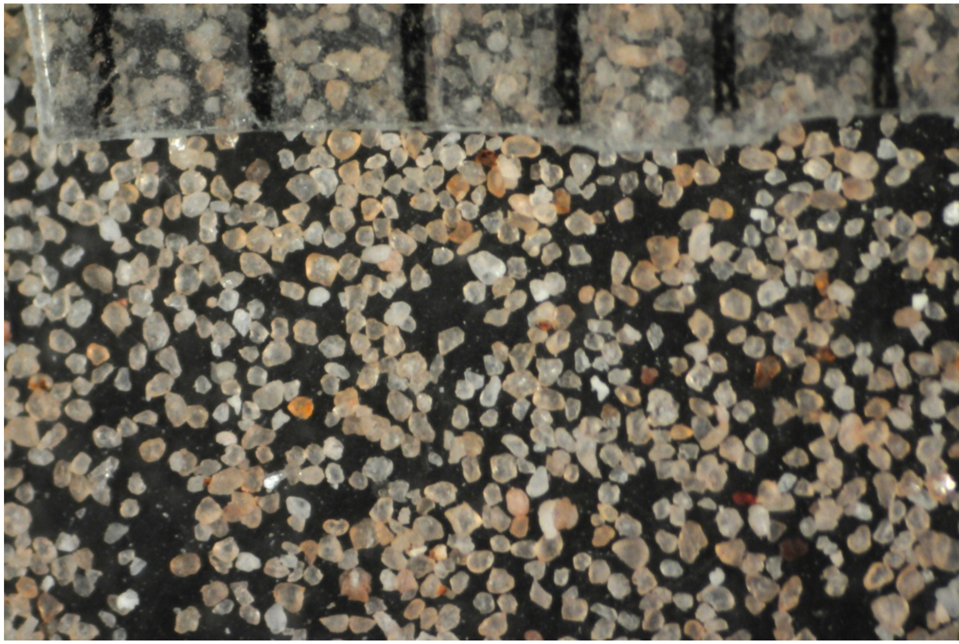
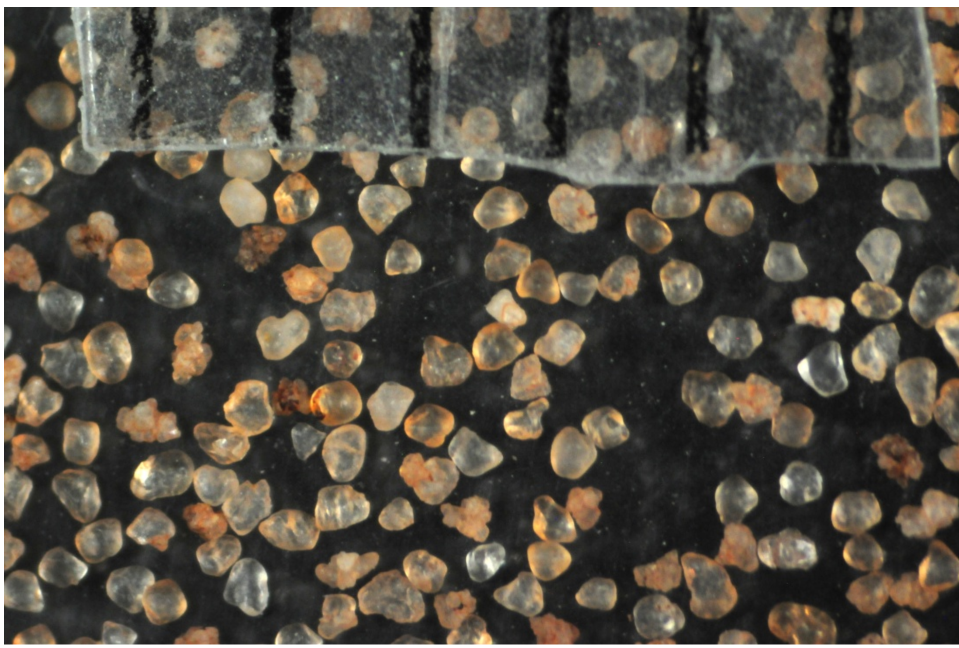


FS-33 No. 140

FS-34 No. 50



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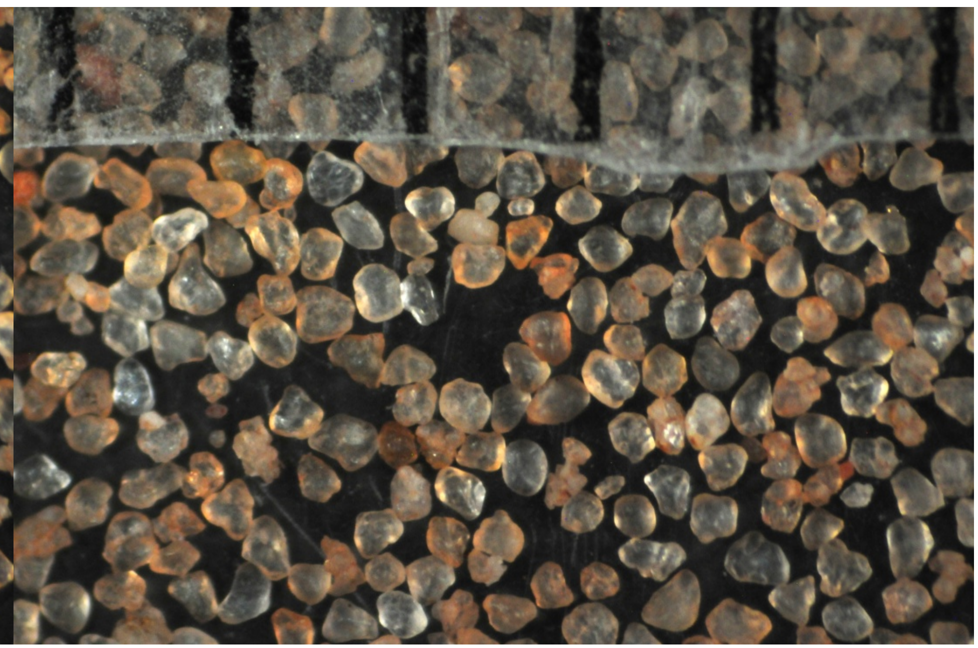

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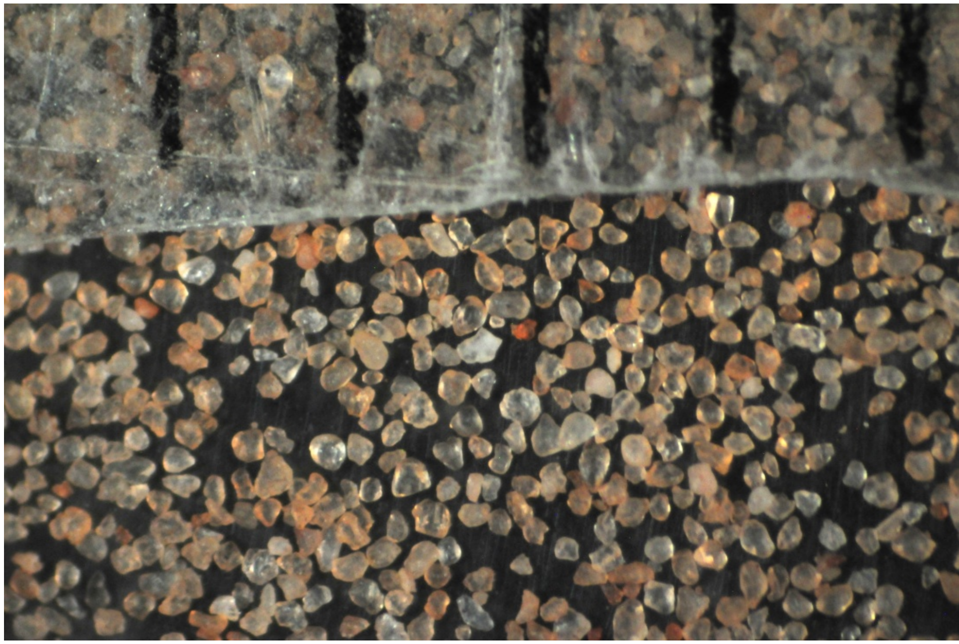

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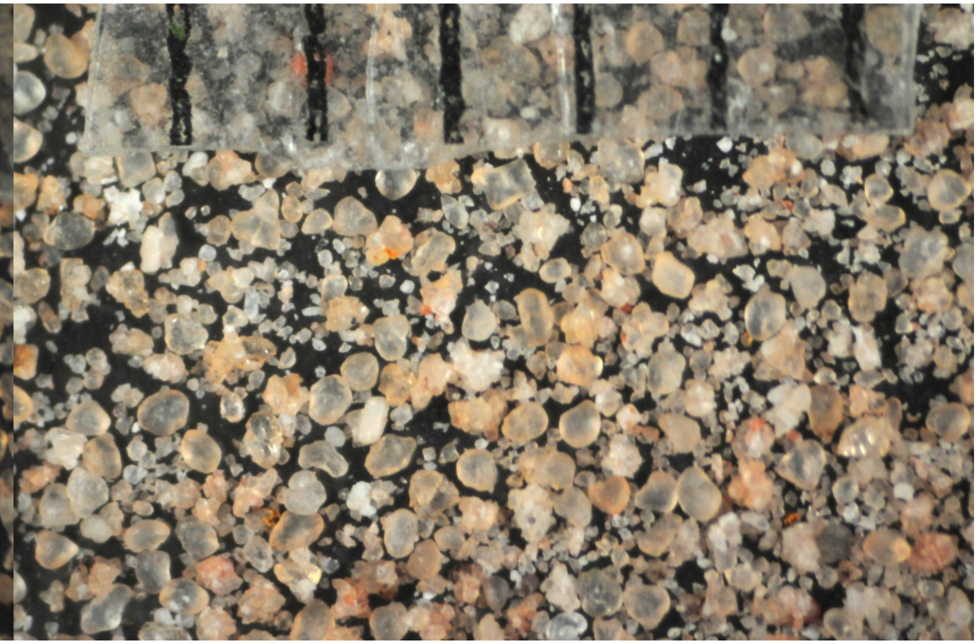

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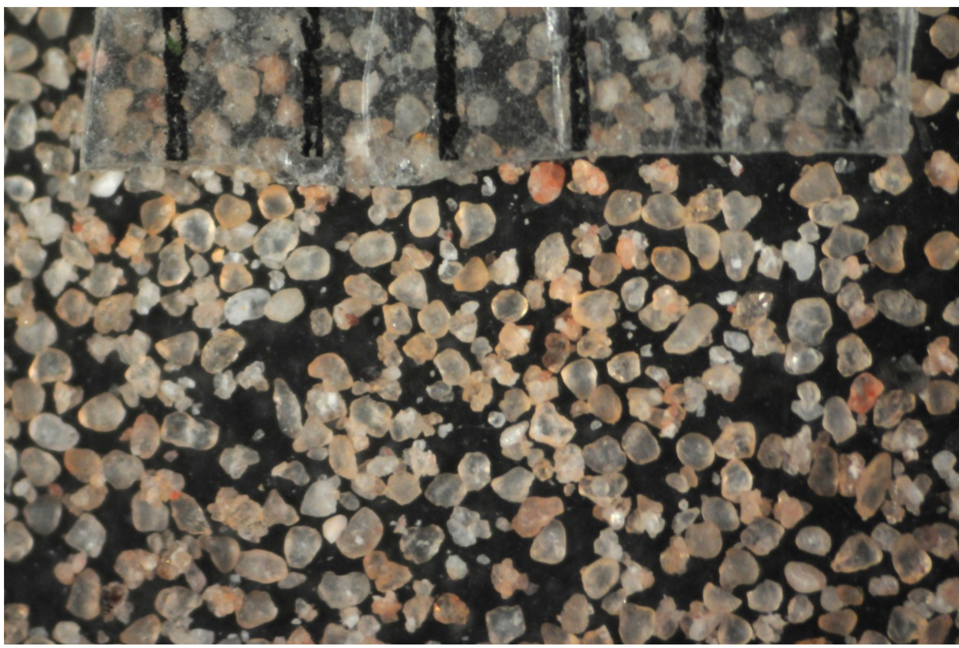

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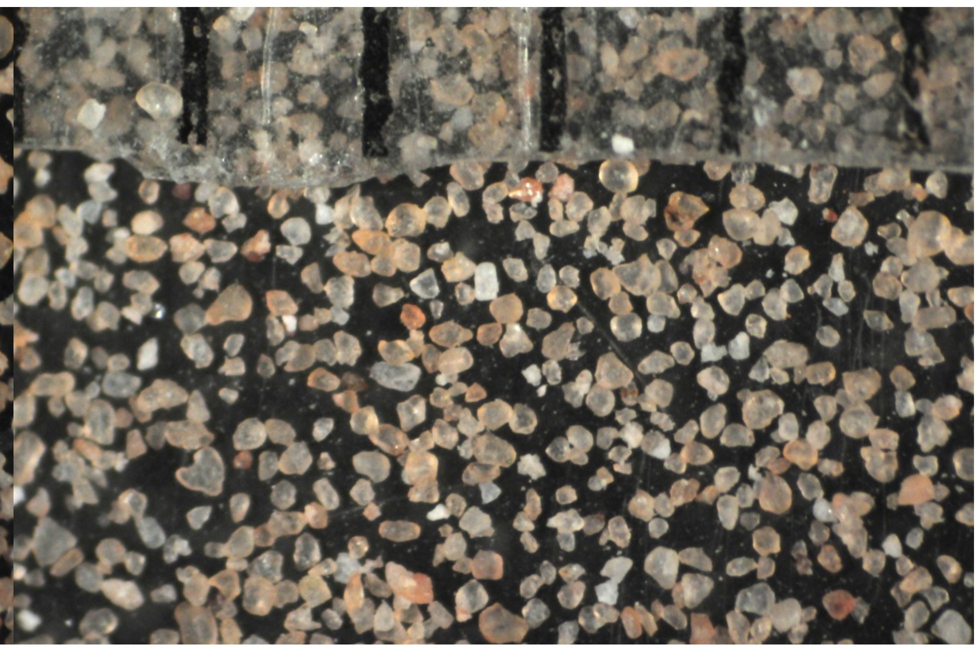
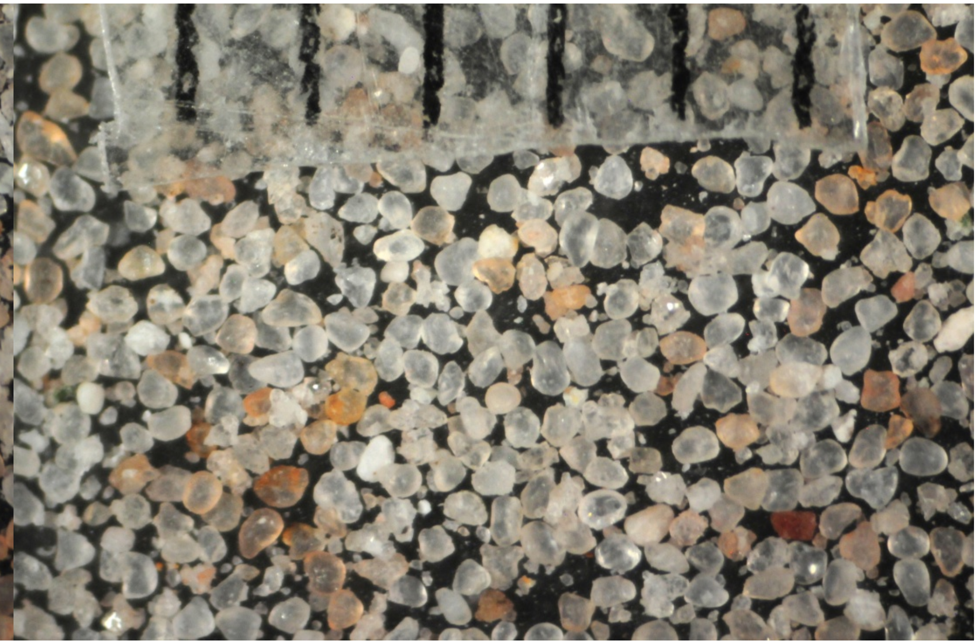


FS-35 No. 140


FS-36 No. 50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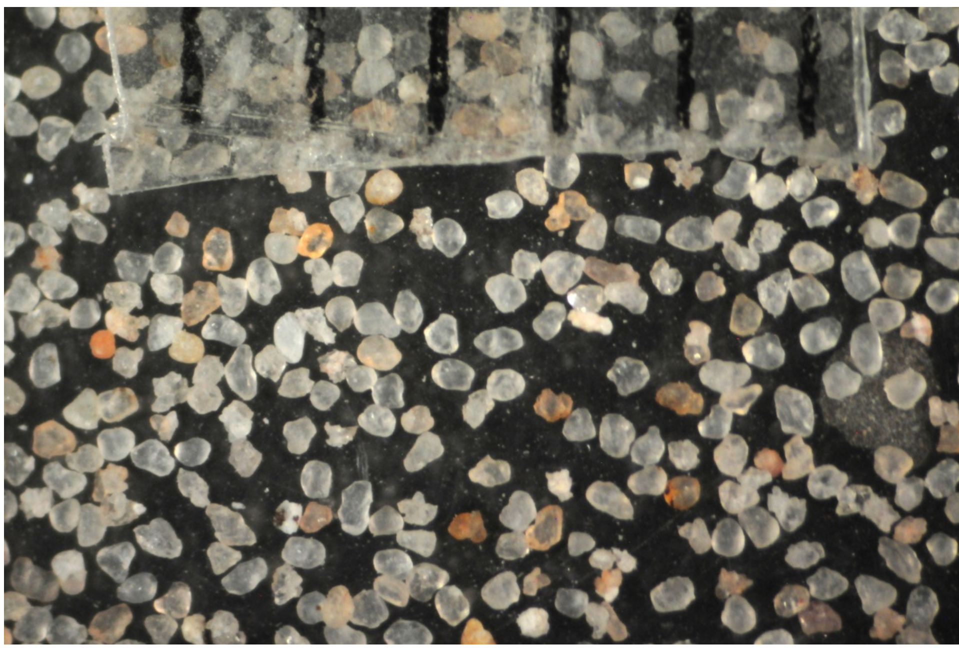
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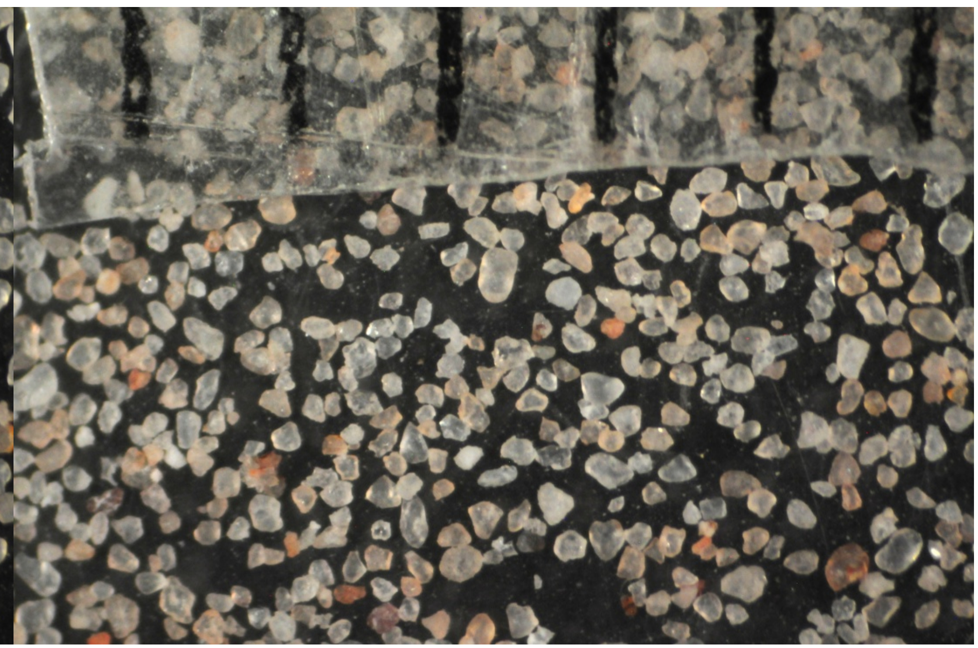
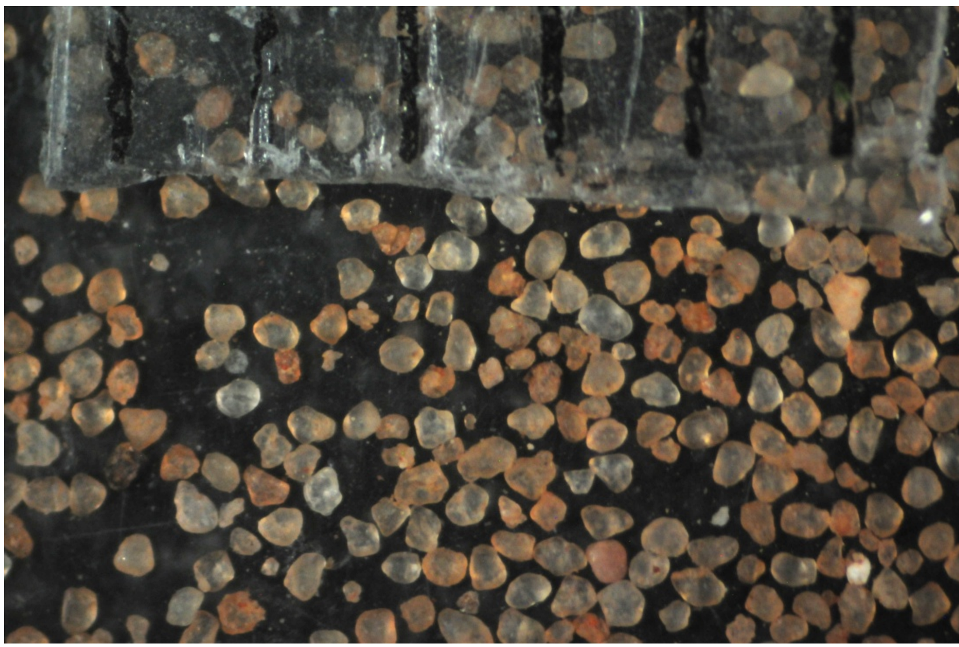

FS-36 No. 140


FS-37 No. 50


FS-37 No. 60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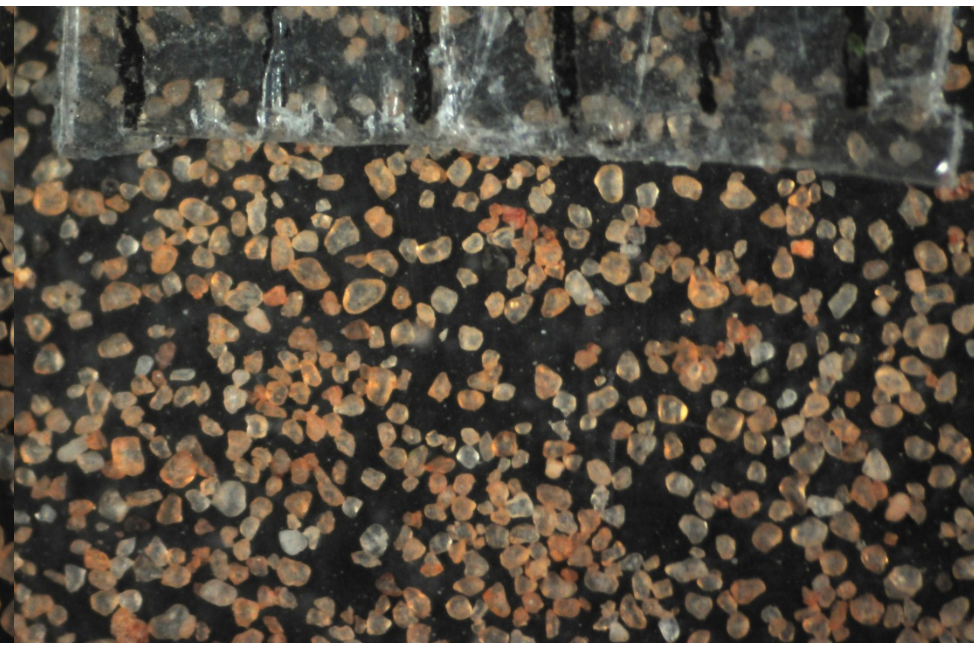
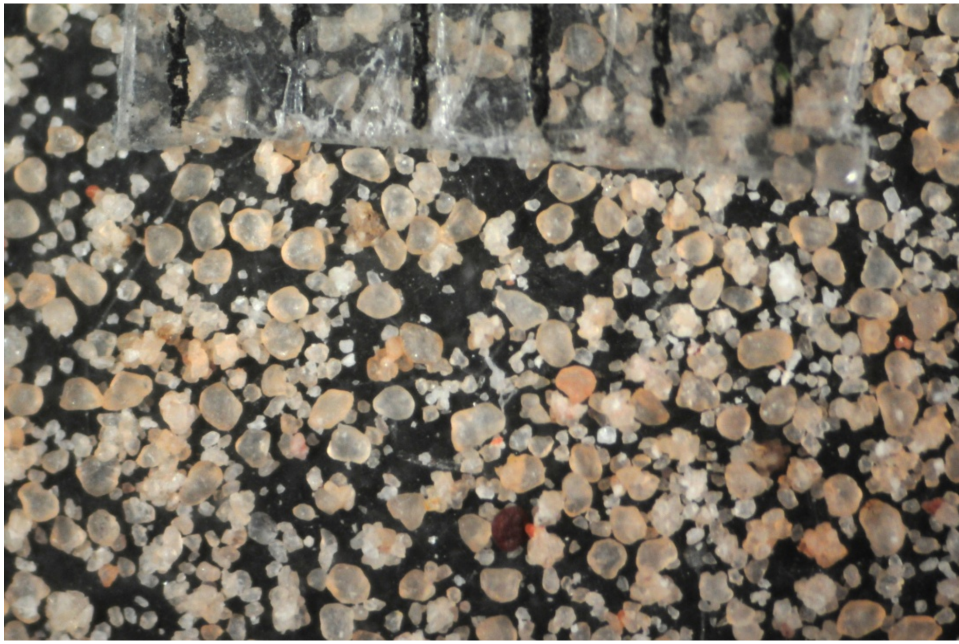

FS-37 No. 140


FS-38 No. 50


FS-38 No. 60


FS-38 No. 70


FS-38 No. 140



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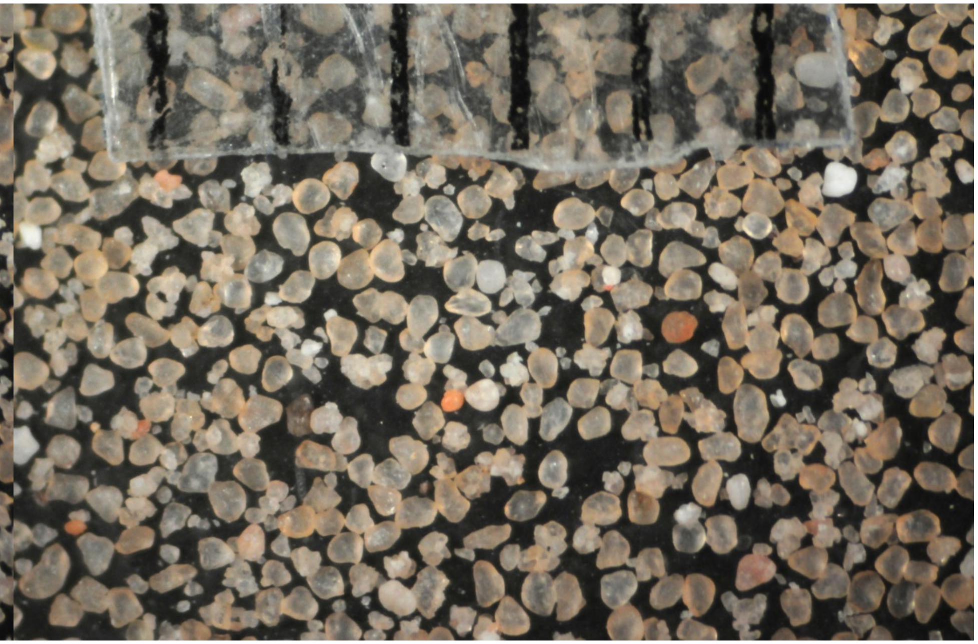

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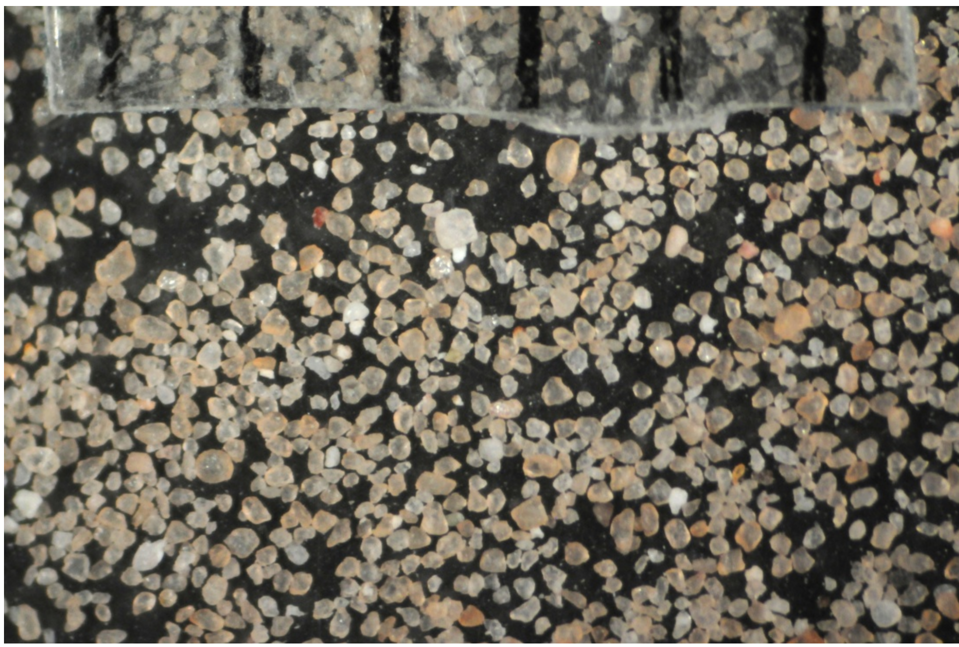

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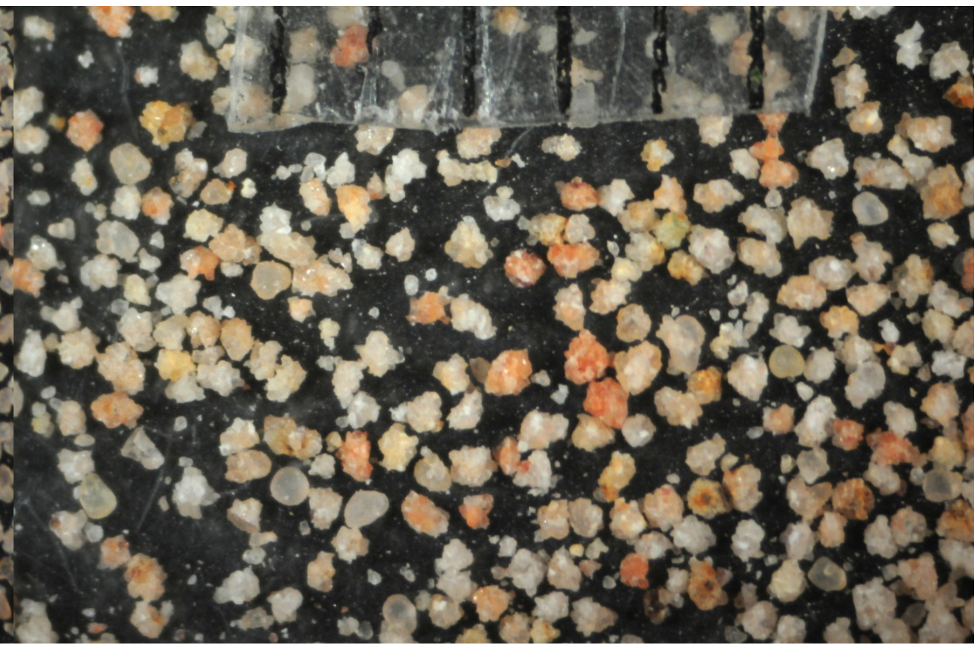
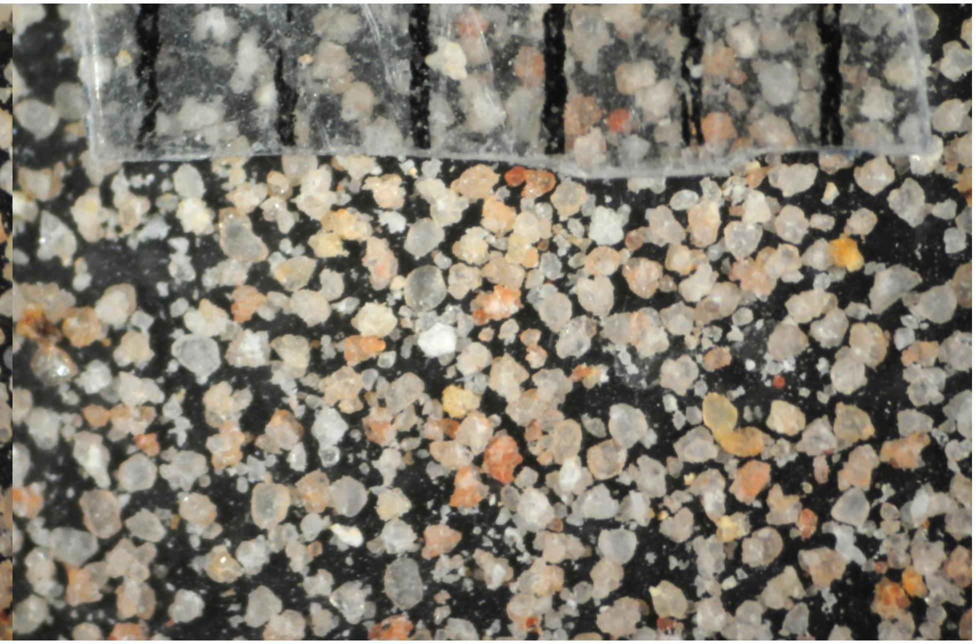


FS-40 No. 50


FS-40 No. 60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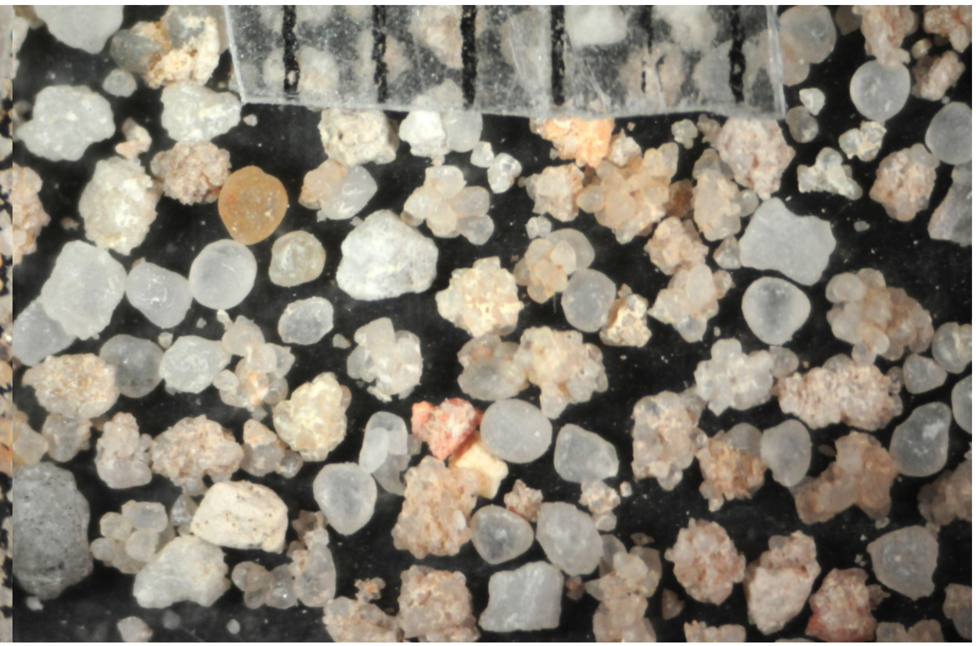
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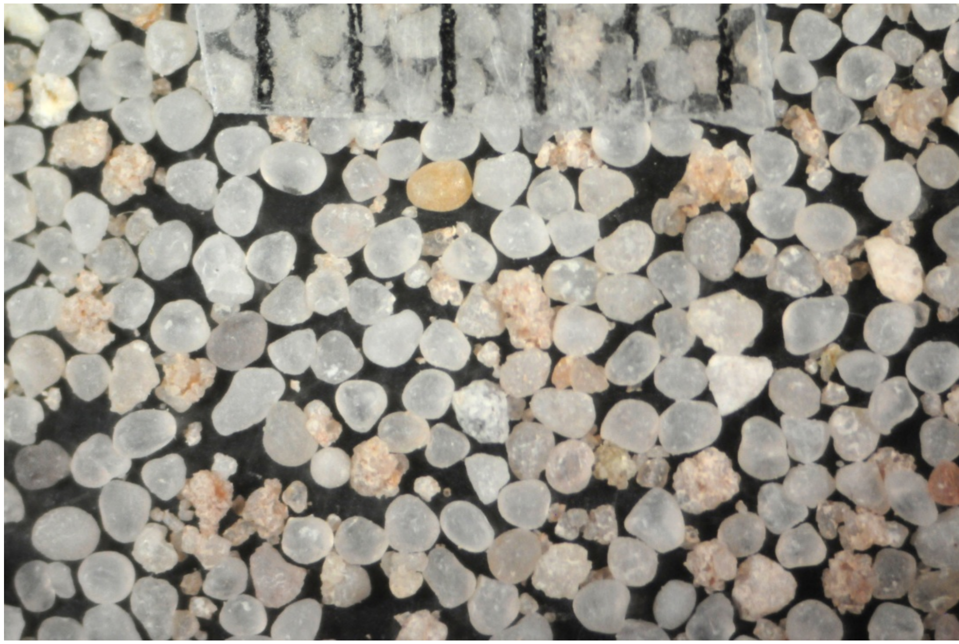
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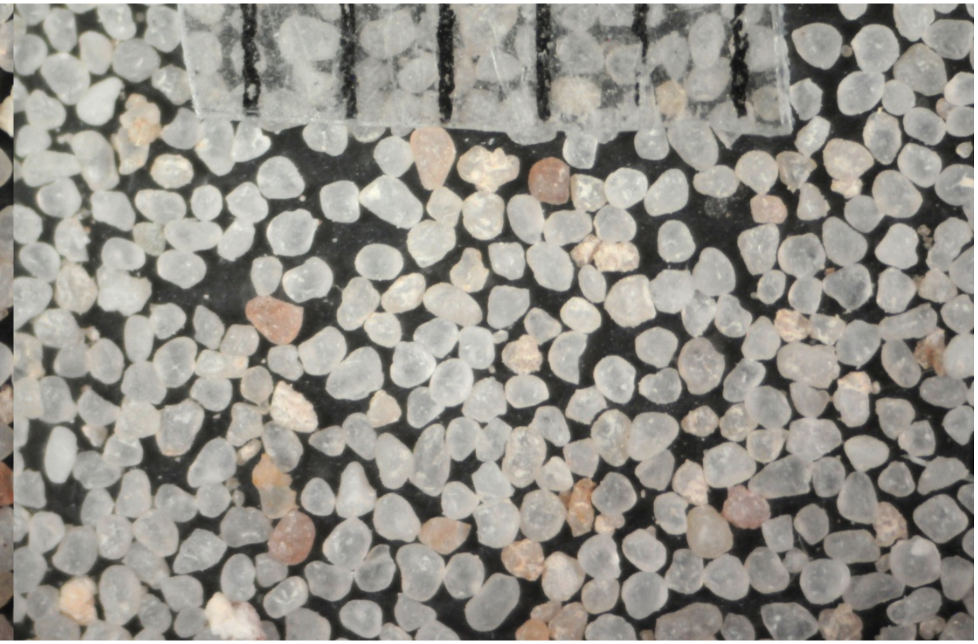
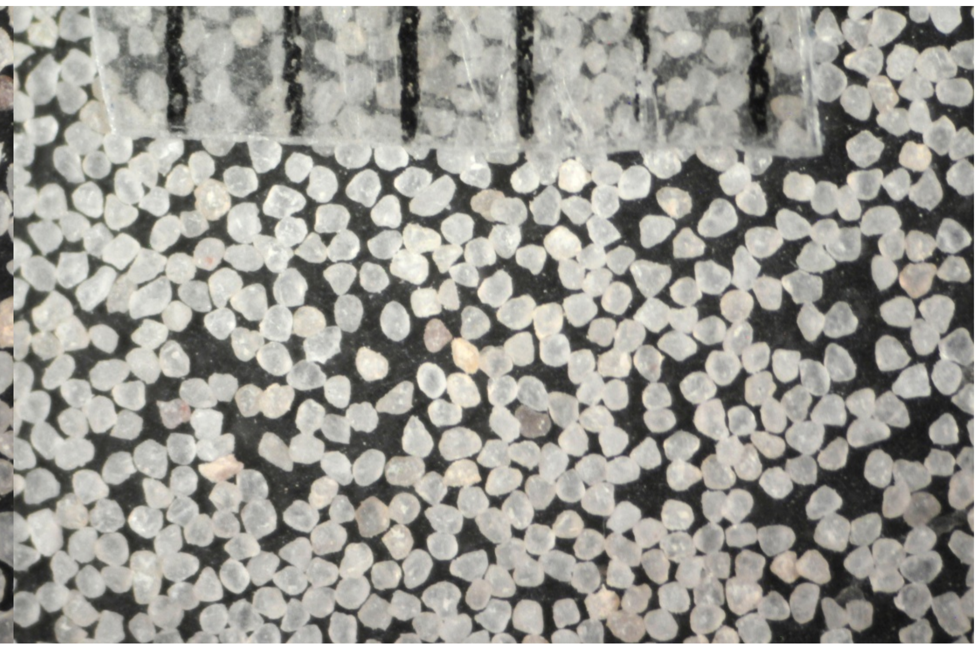
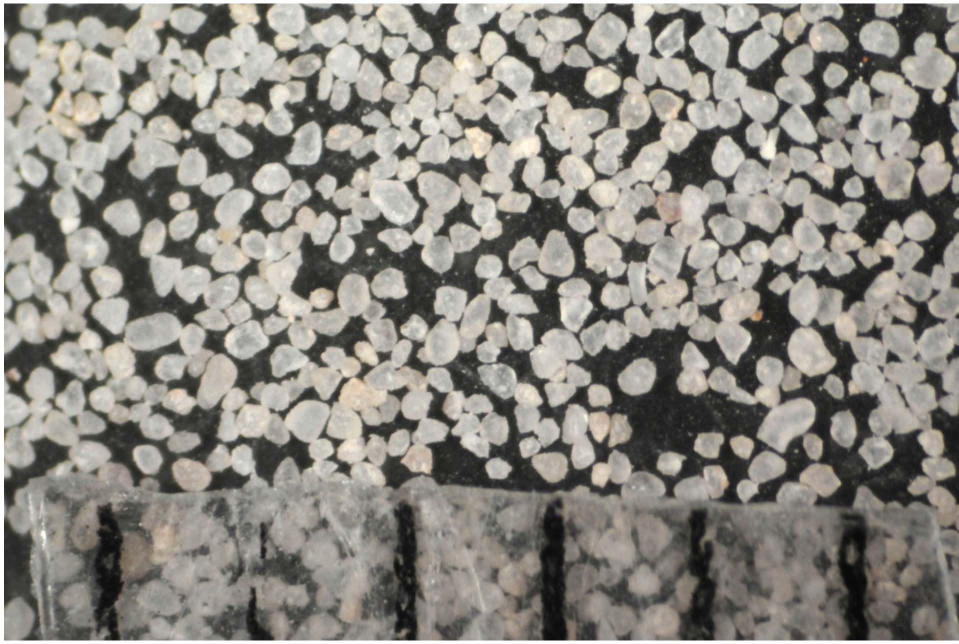
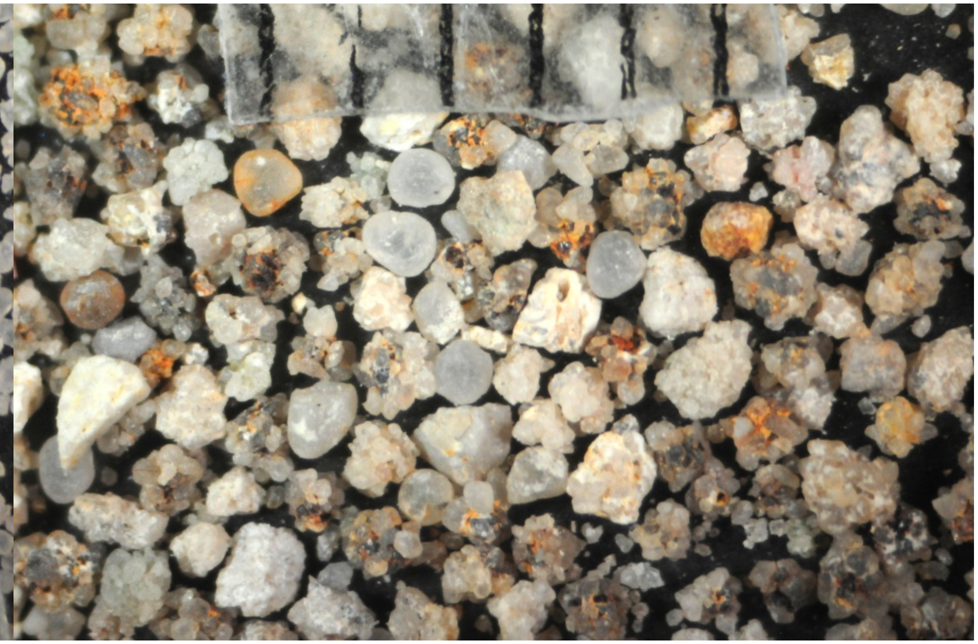

FS-43 No. 50


FS-43 No. 60


FS-43 No. 70



FS-43 No. 140



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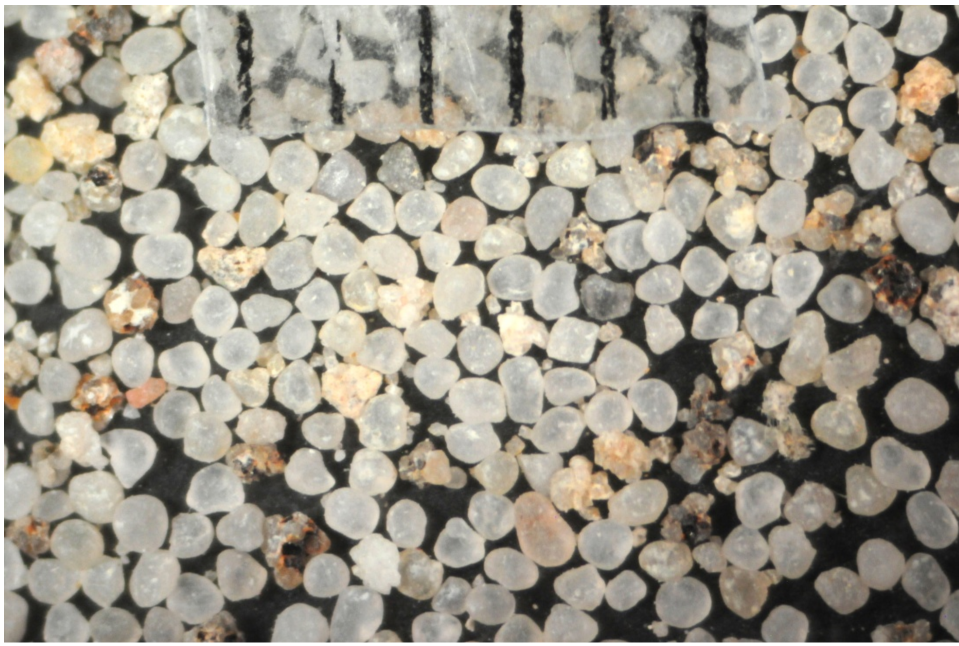

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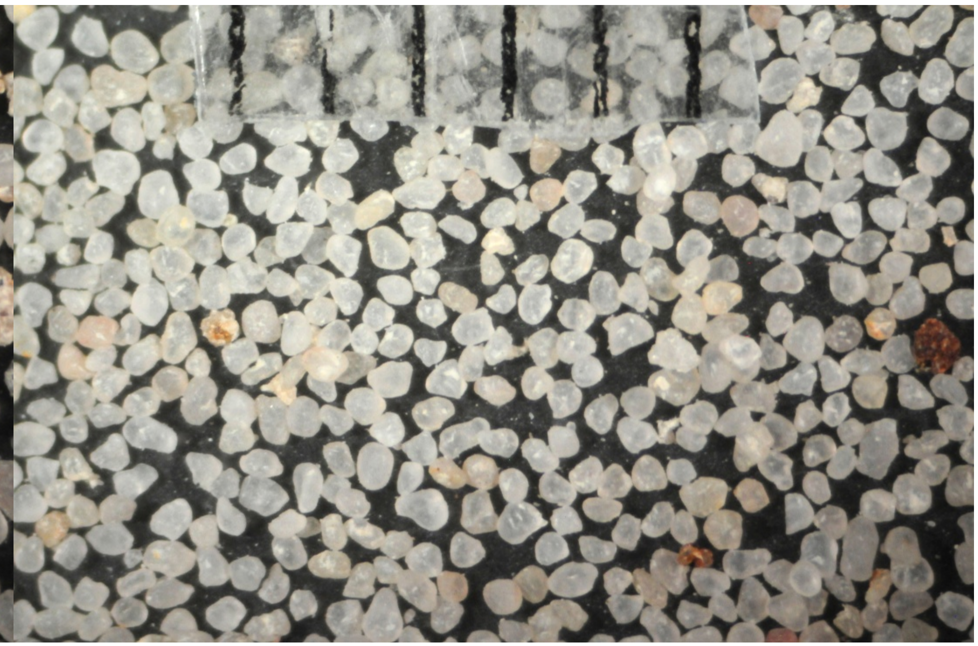

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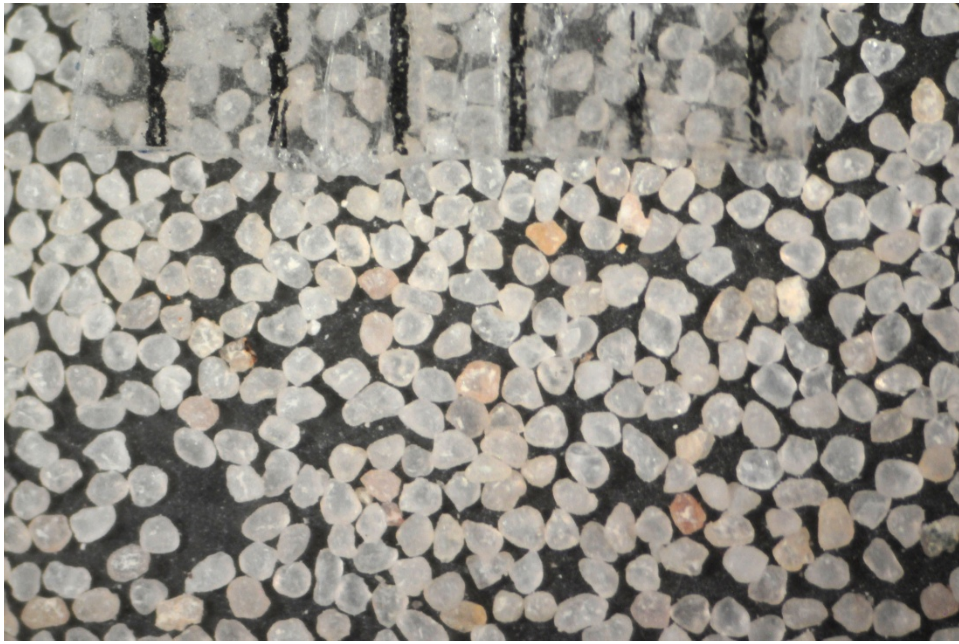
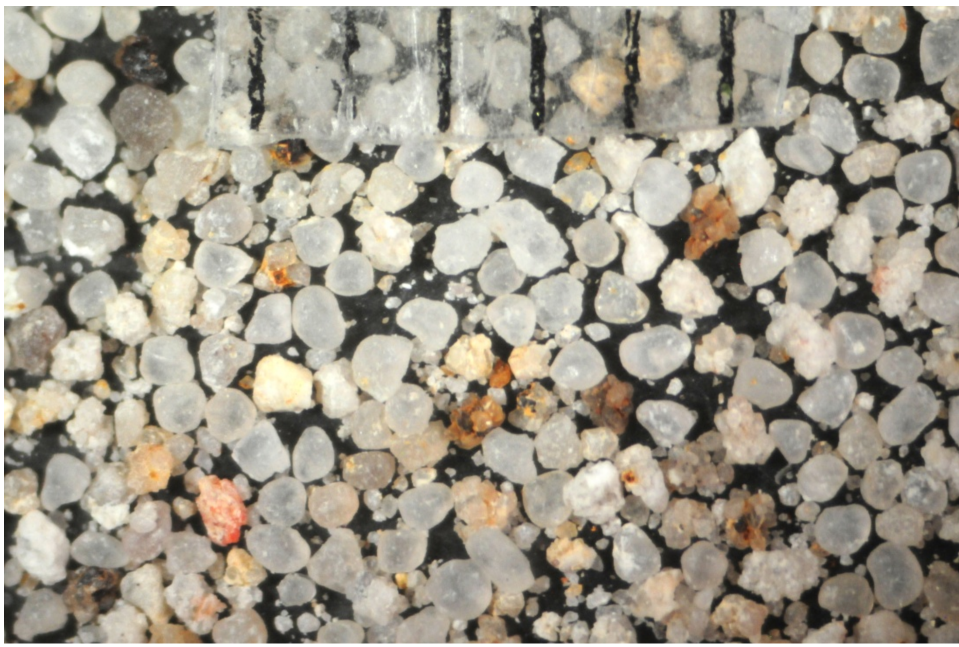


FS-44 No. 60

FS-44 No. 70



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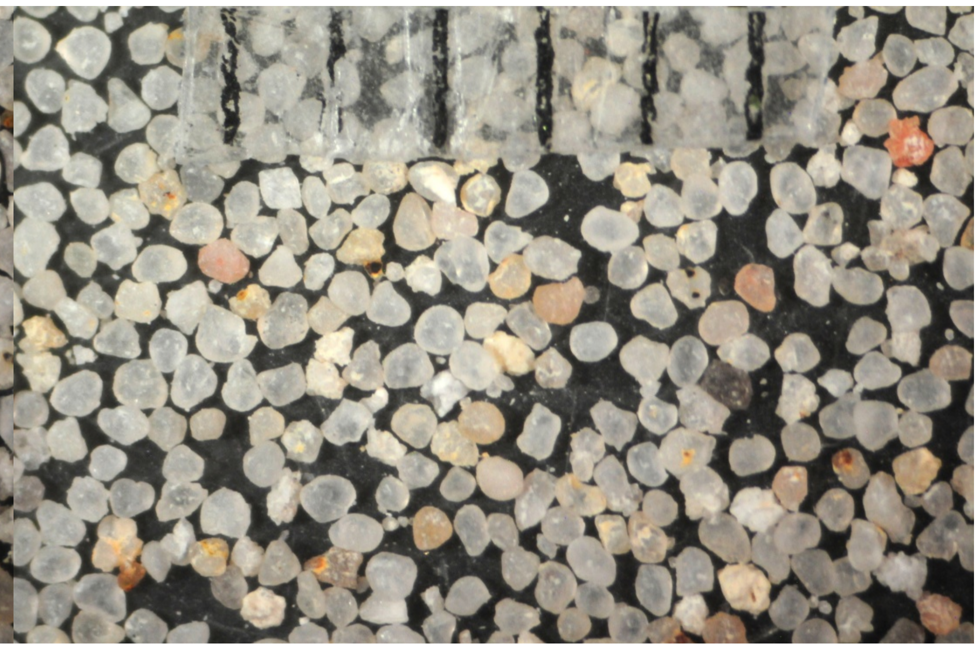

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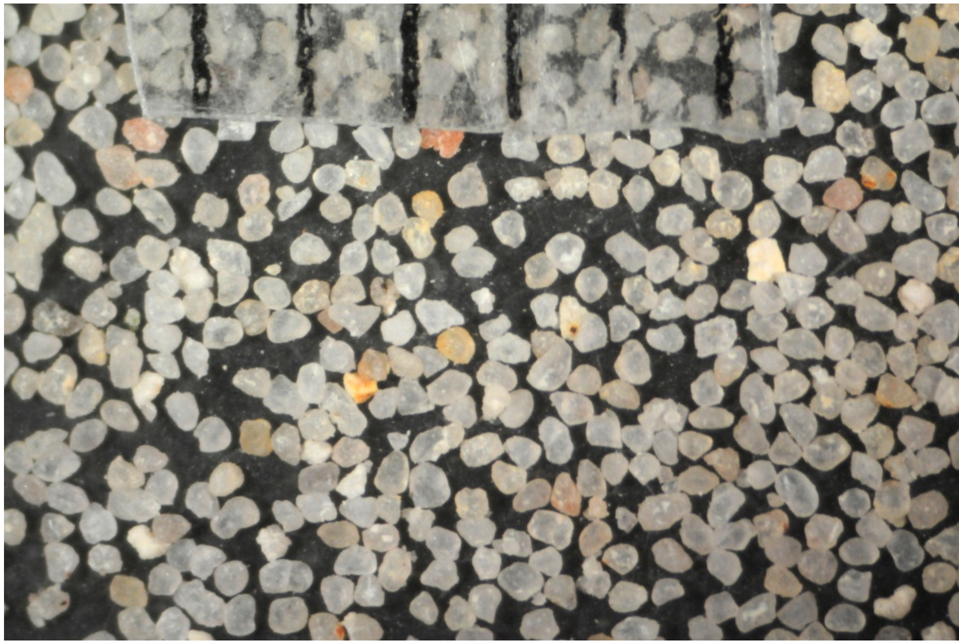
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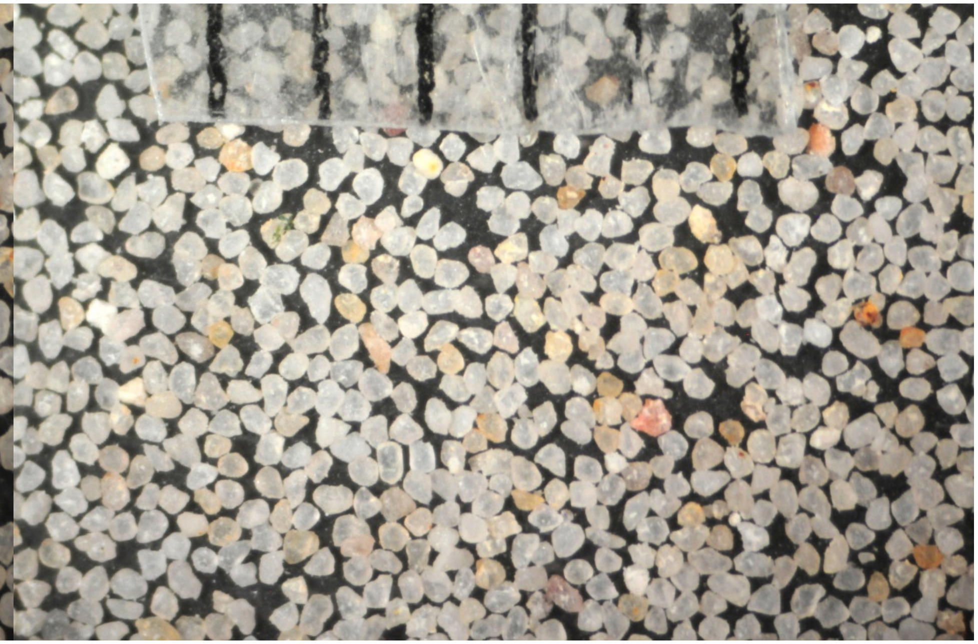
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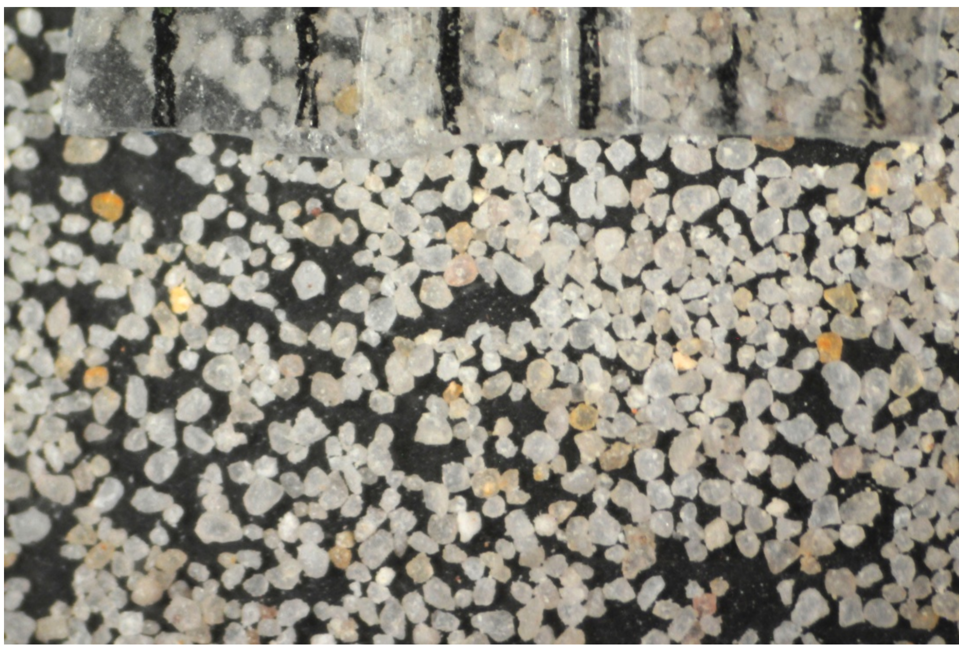
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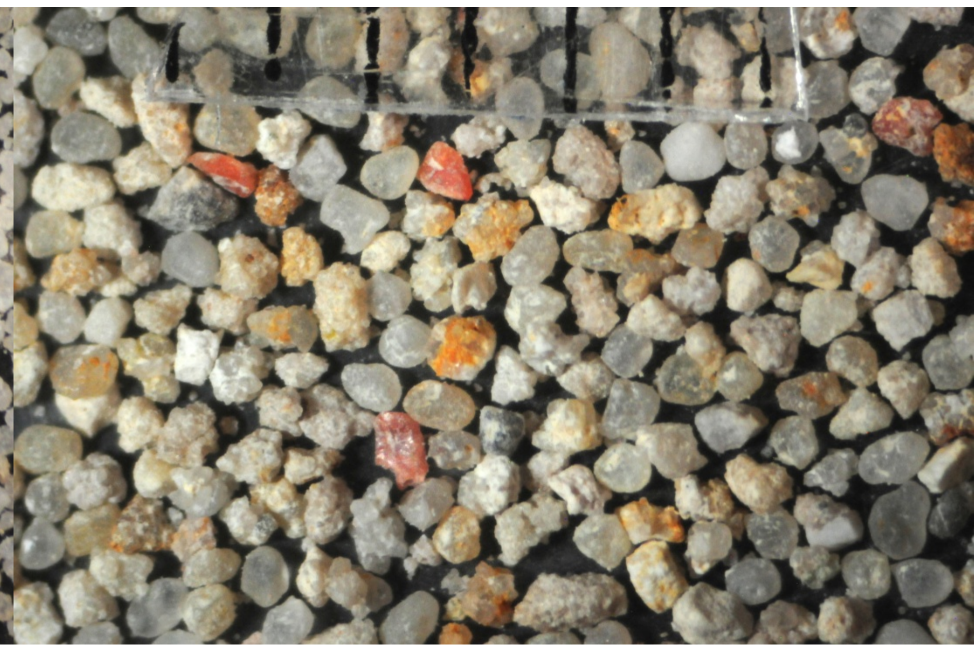
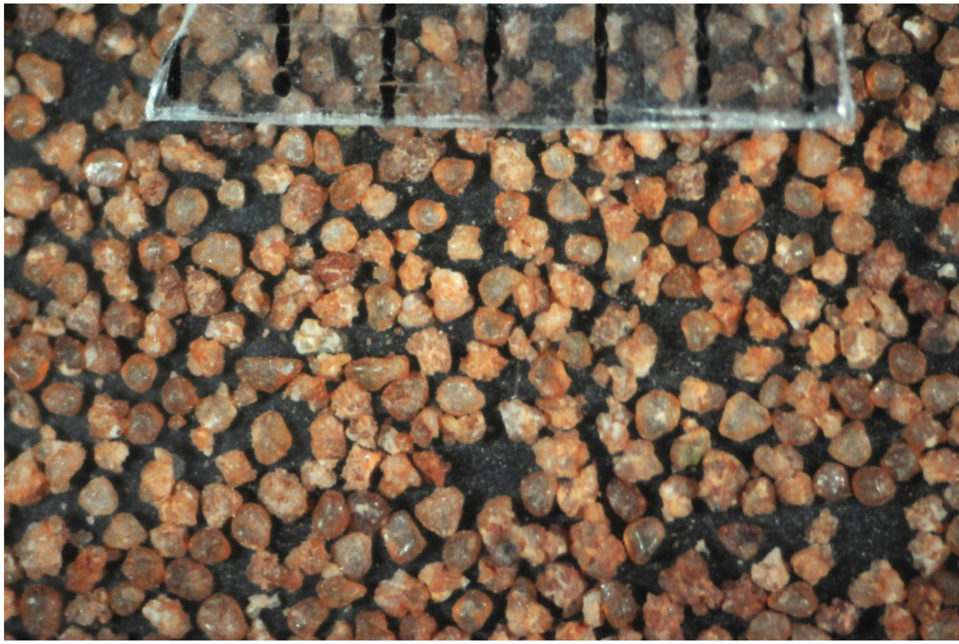

FS-46 No. 40


FS-46 No. 50


FS-46 No. 60


FS-46 No. 70

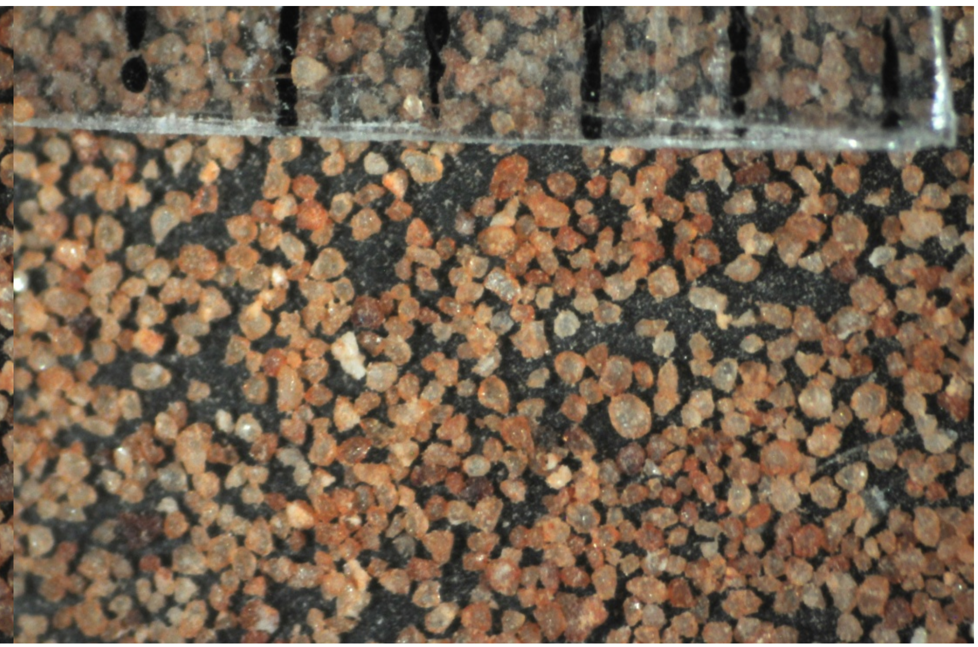

FS-46 No. 140



FS-47 No. 50

FS-47 No. 60

FS-47 No. 70



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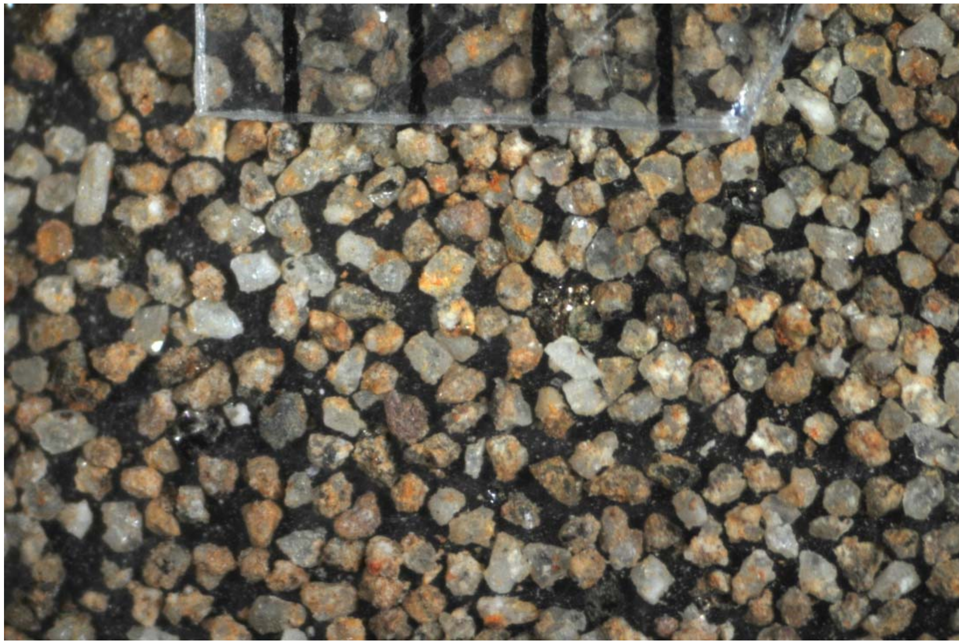

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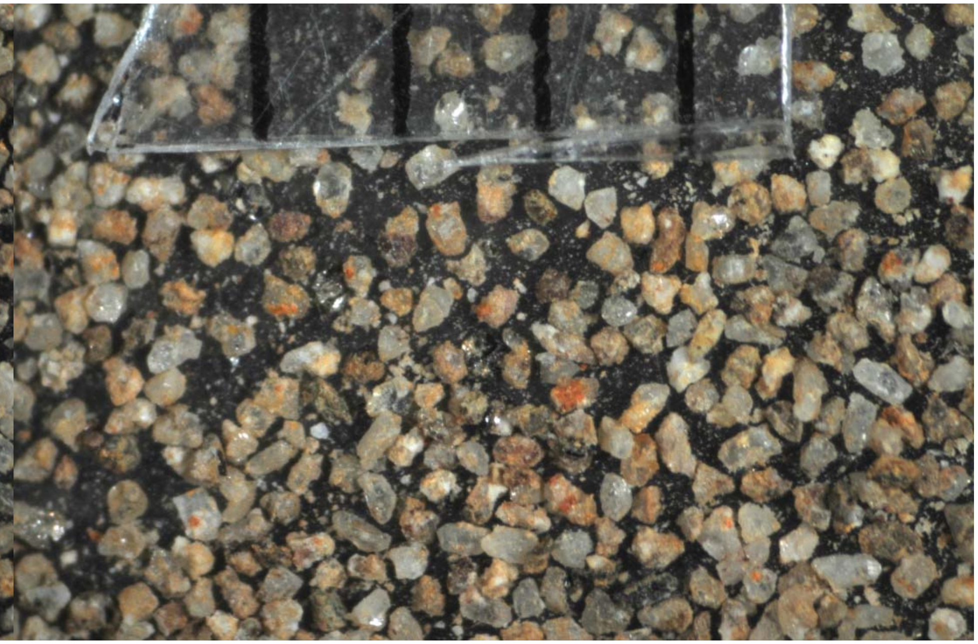

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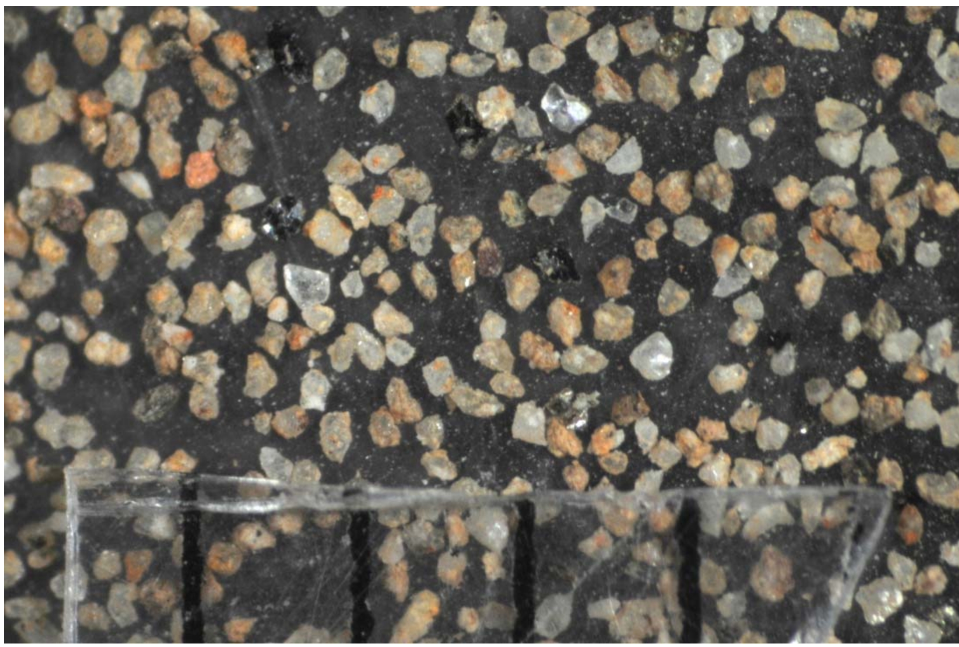
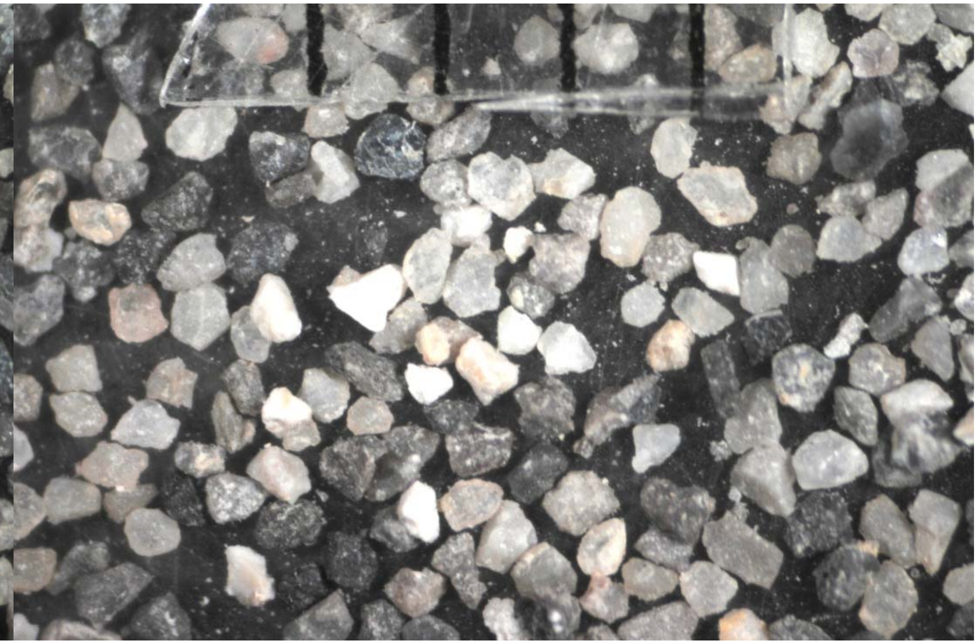


FS-51 No. 140

FS-52 No. 30


FS-52 No. 40


FS-52 No. 50


FS-52 No. 60

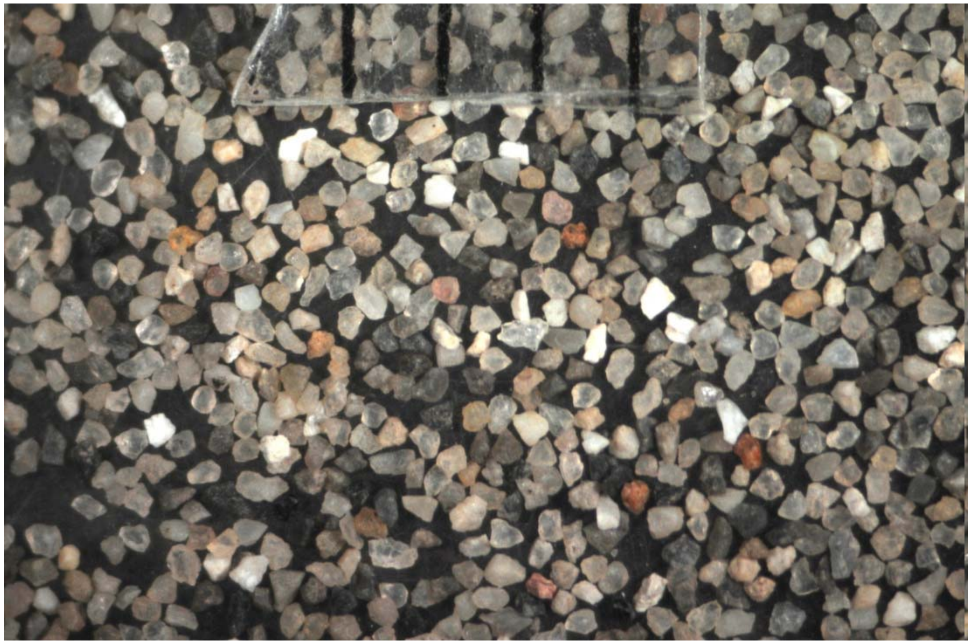

FS-52 No. 70

FS-52 No. 140

FS-53 No. 30

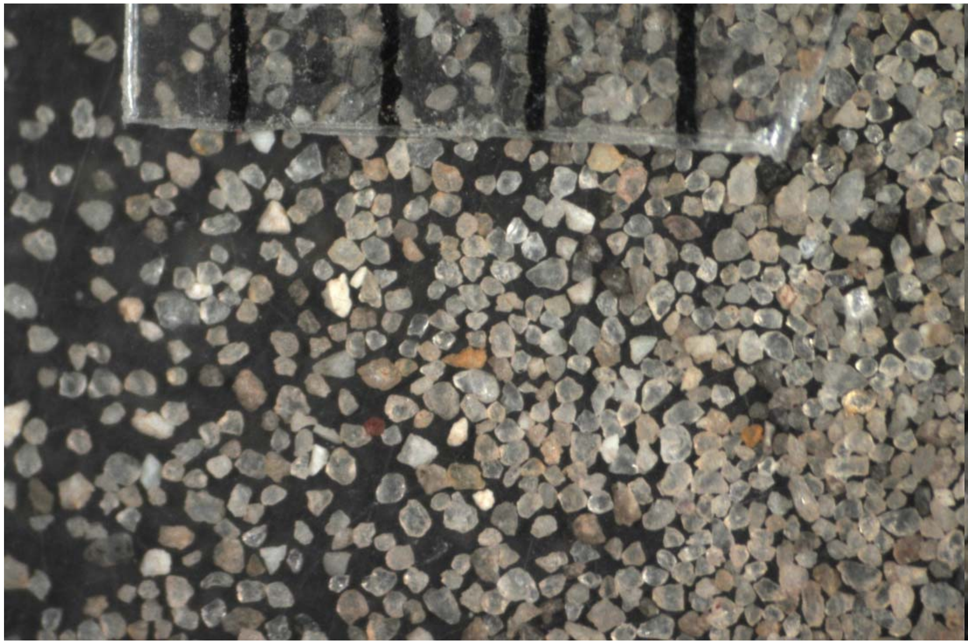
FS-53 No. 40

FS-53 No. 50



FS-53 No. 60

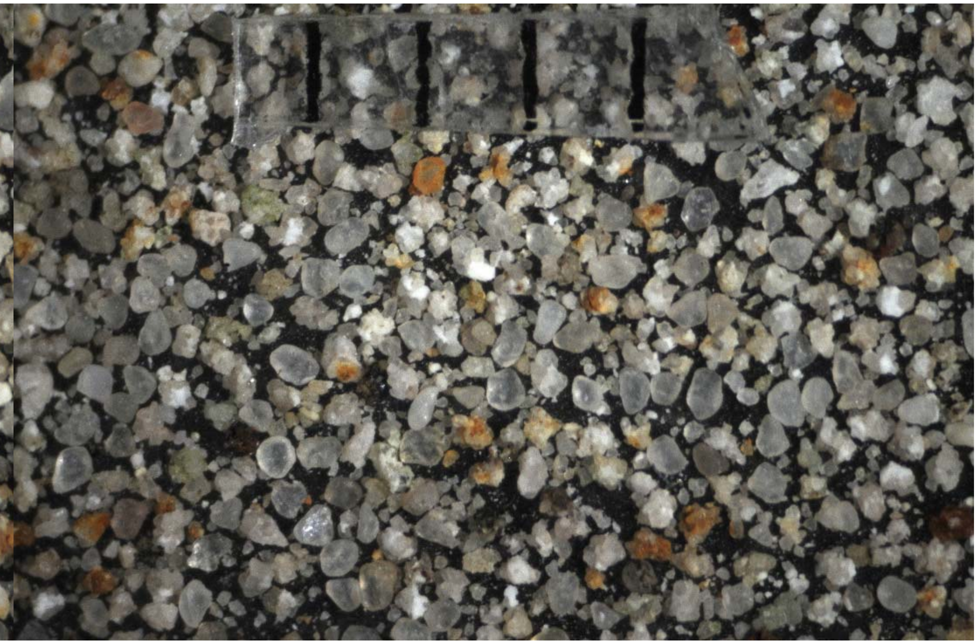
FS-53 No. 70



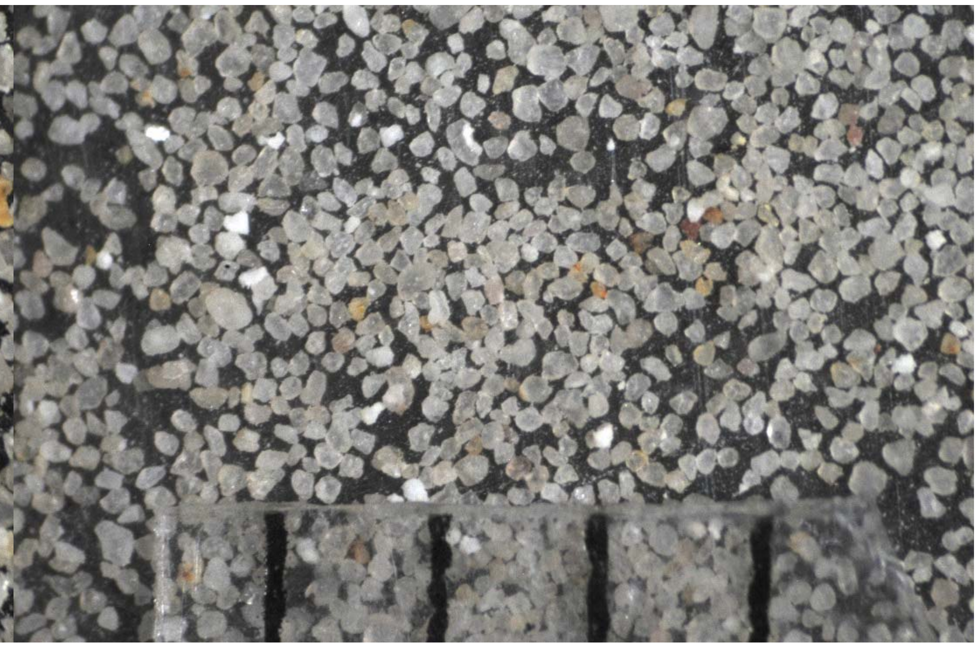
FS-53 No. 140

FS-55 No. 40

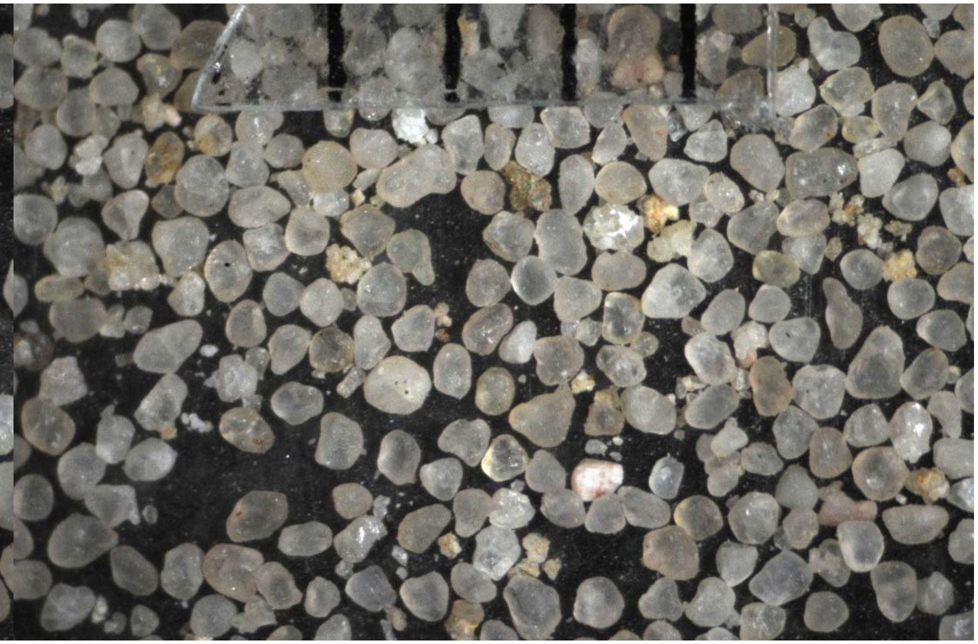

FS-55 No. 50


FS-55 No. 60


FS-55 No. 70


FS-55 No. 140


FS-56 No. 40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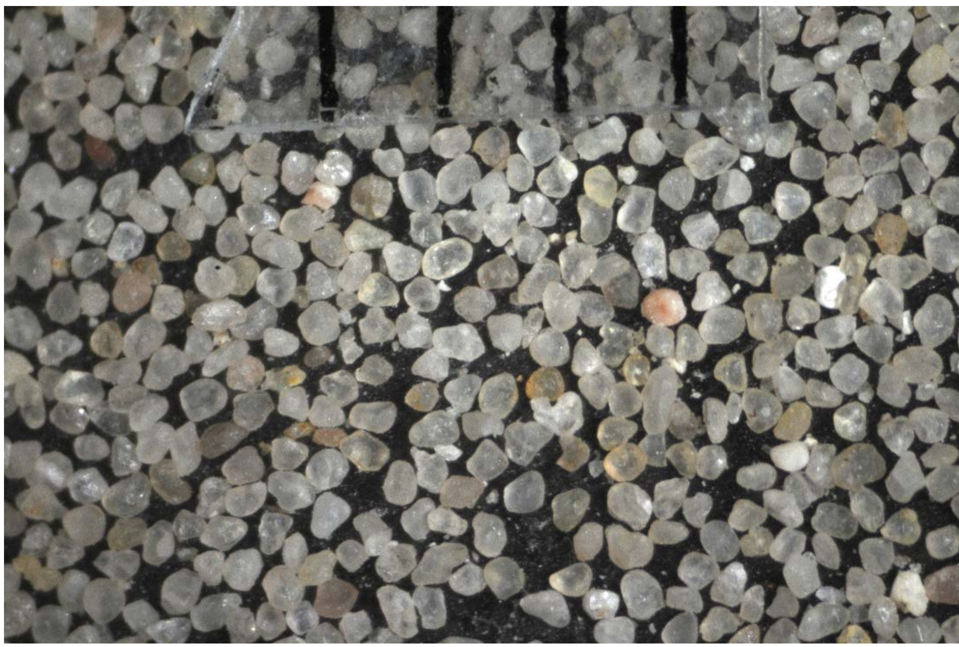
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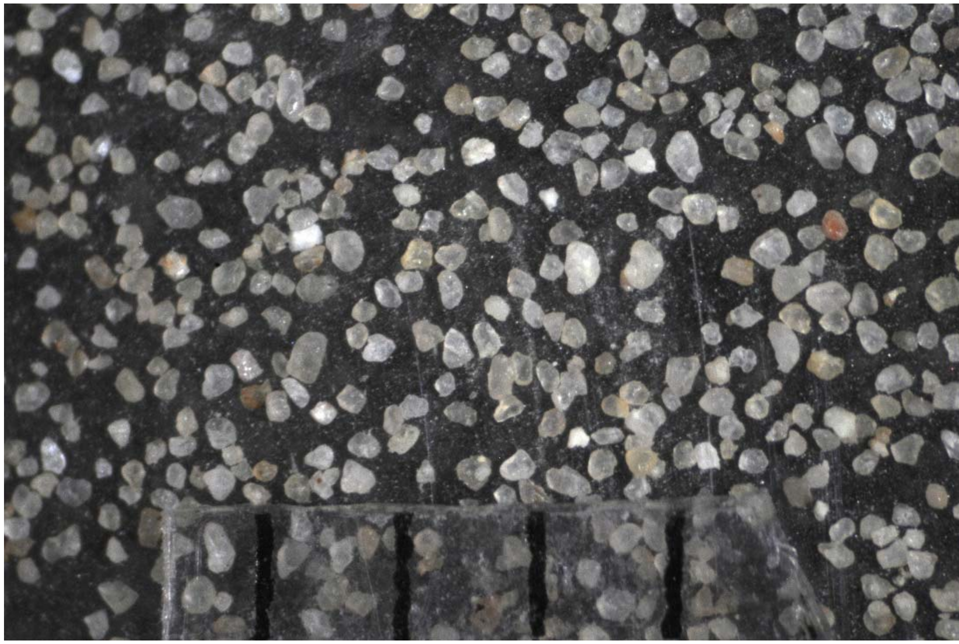
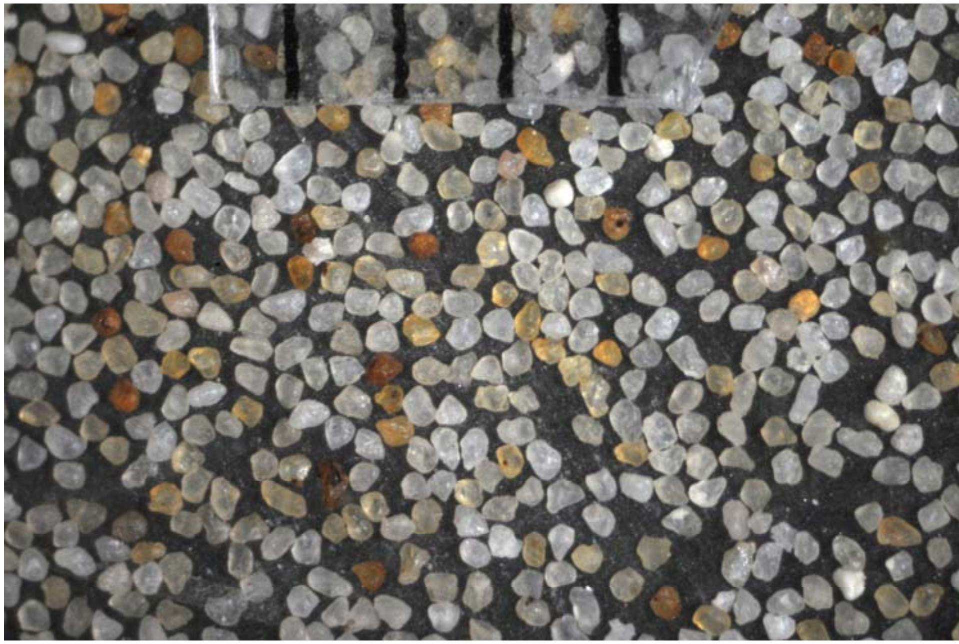
FS-56 No. 70


FS-56 No. 140


FS-57 No. 40


FS-57 No. 50


FS-57 No. 60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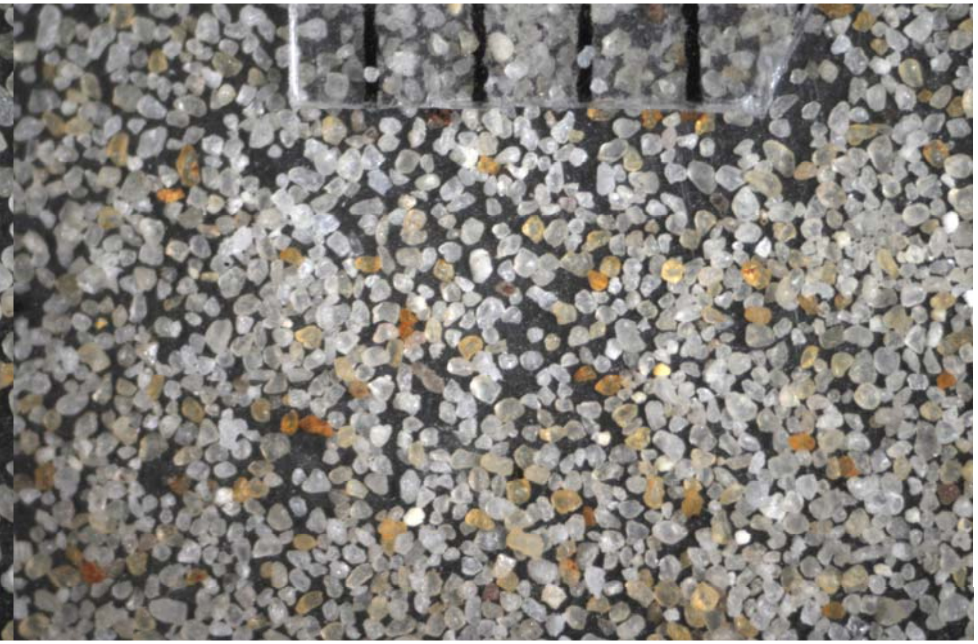
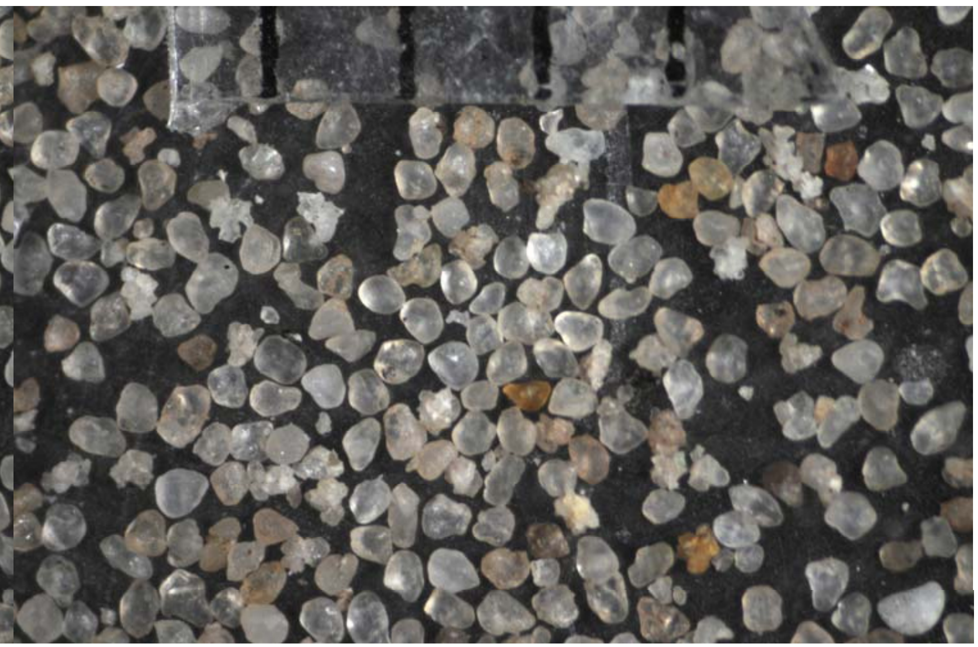
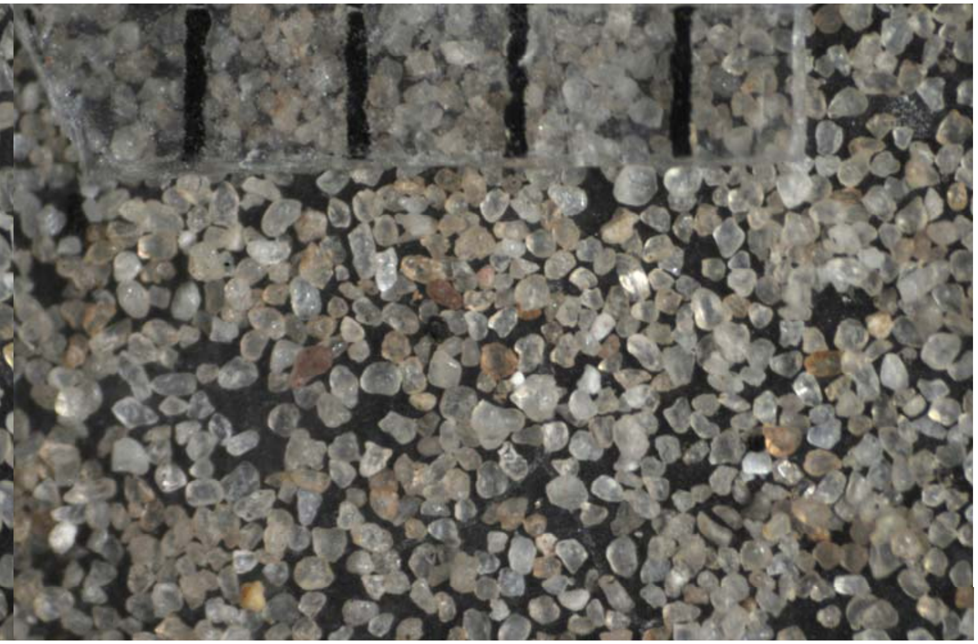

FS-57 No. 140


FS-58 No. 50


FS-58 No. 60

FS-58 No. 70



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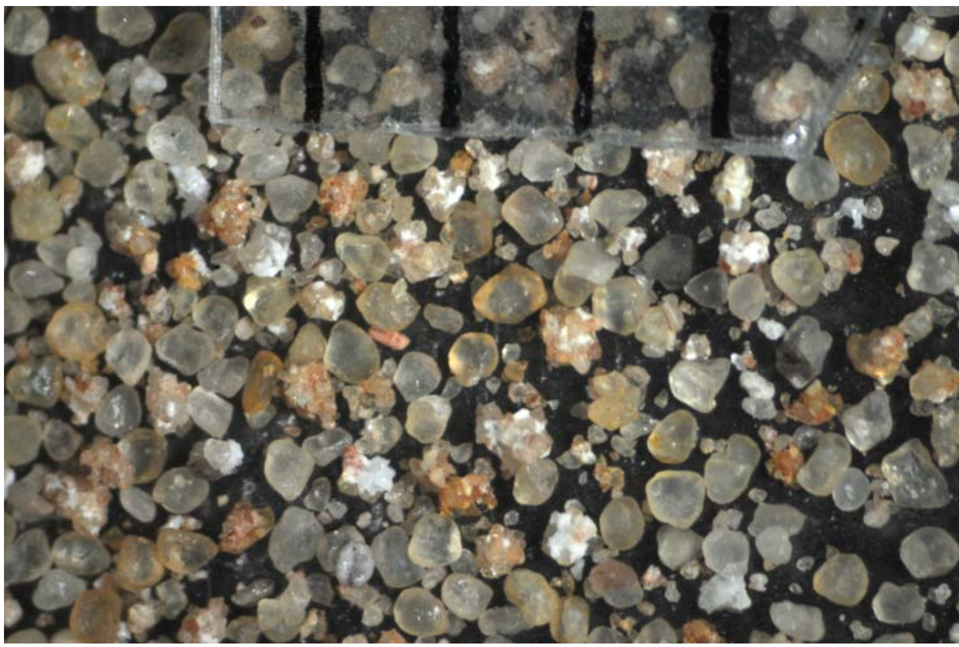
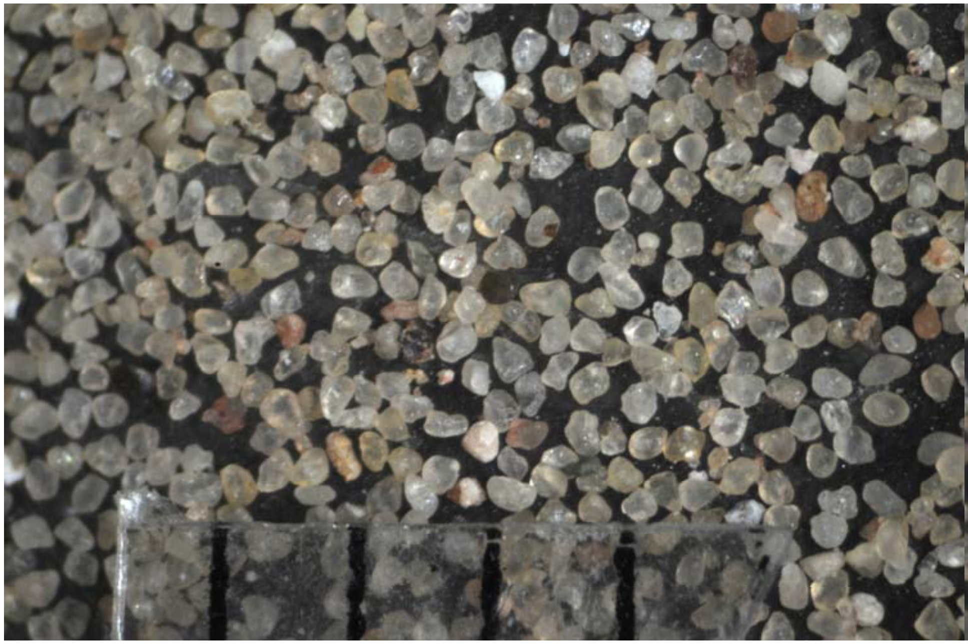


FS-59 No. 50

FS-59 No. 60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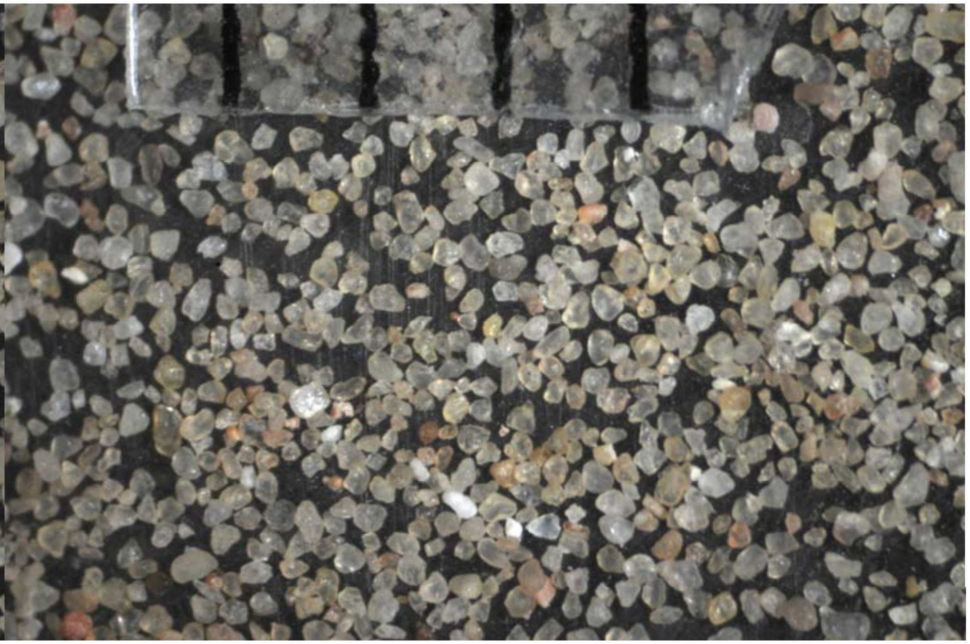
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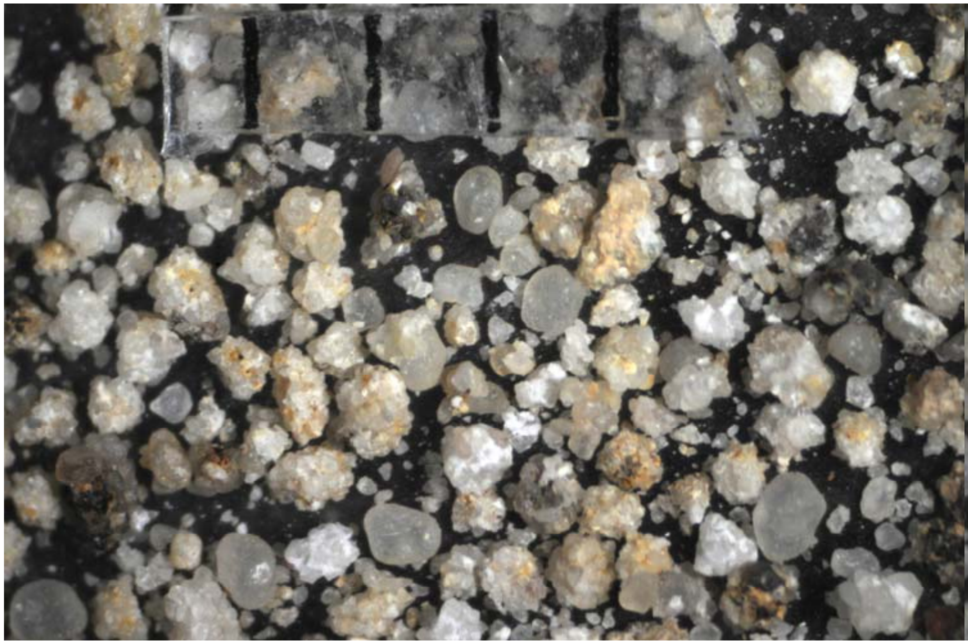
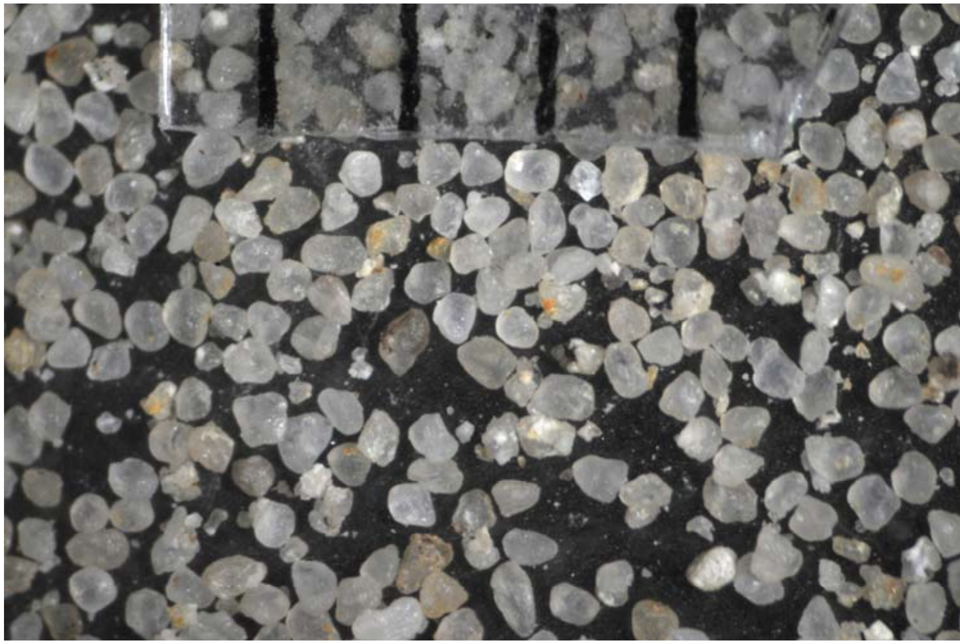

FS-60 No. 40


FS-60 No. 50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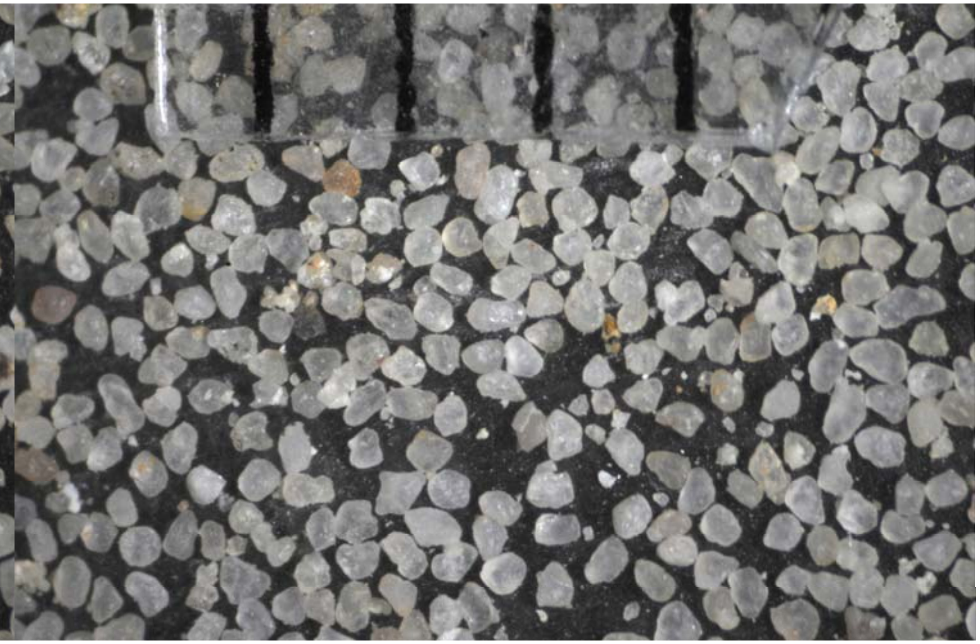
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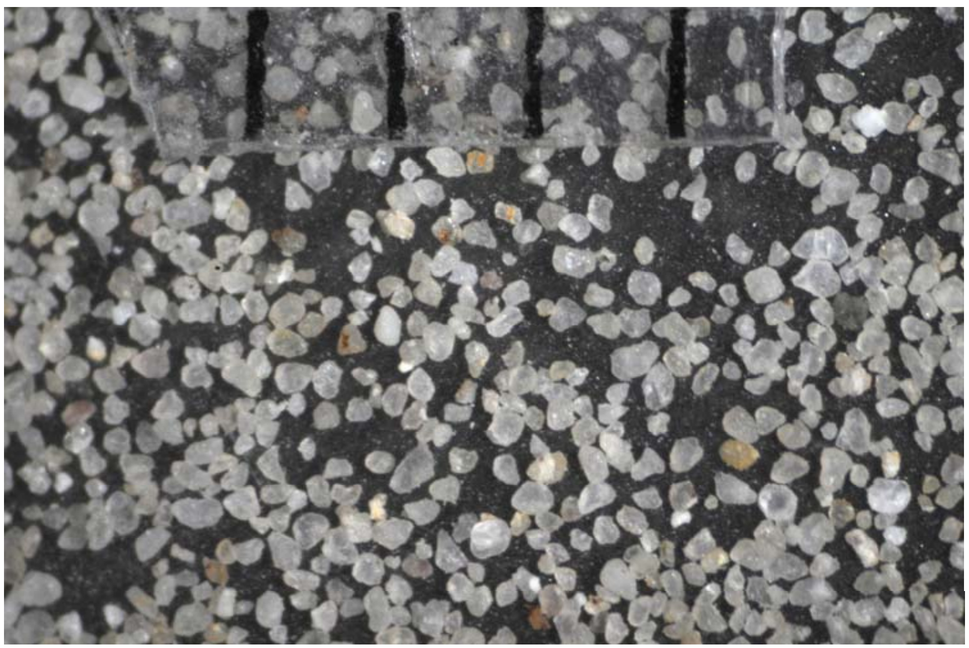
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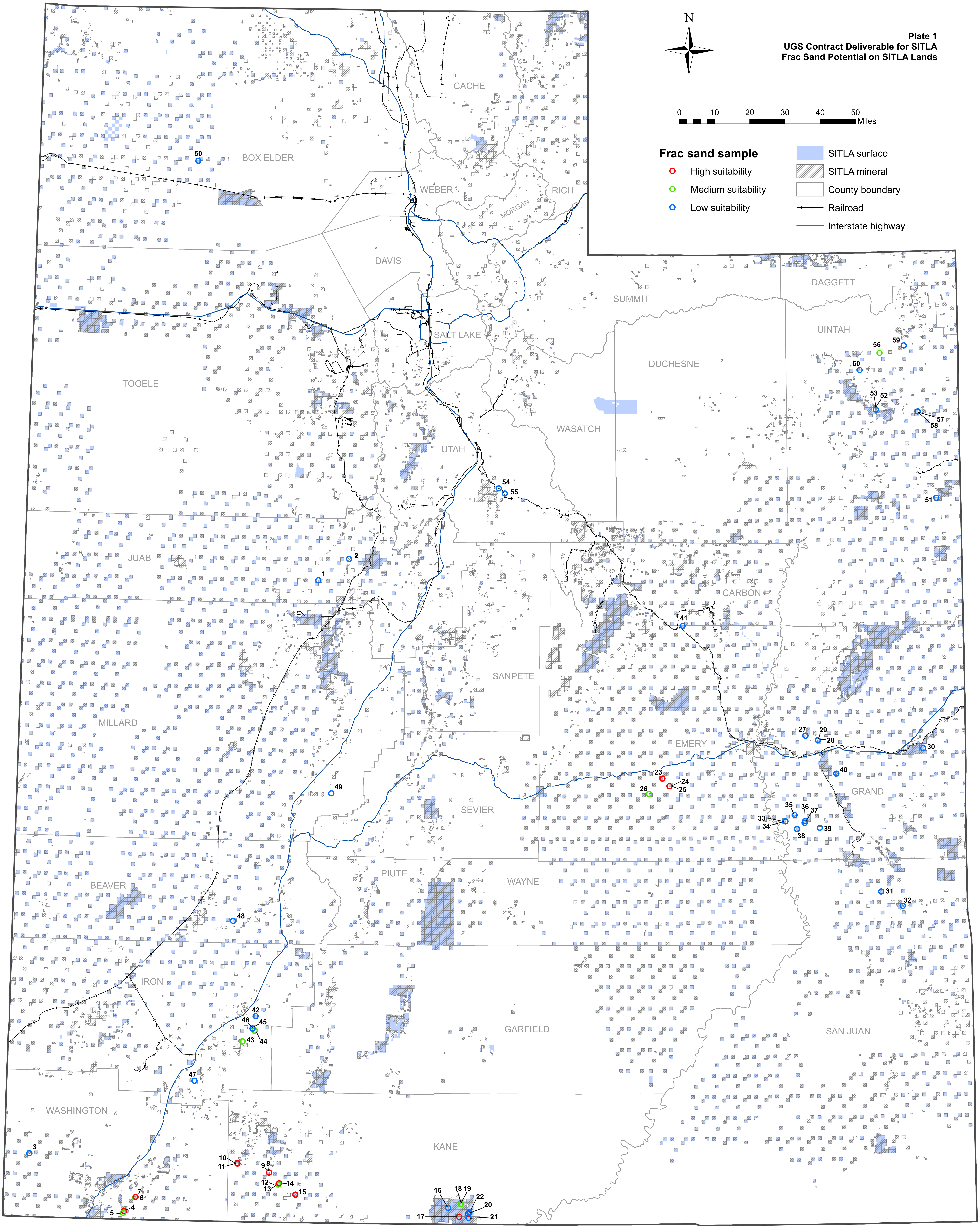

FRAC SAND SAMPLE LOCATIONS AND SUITABILITY