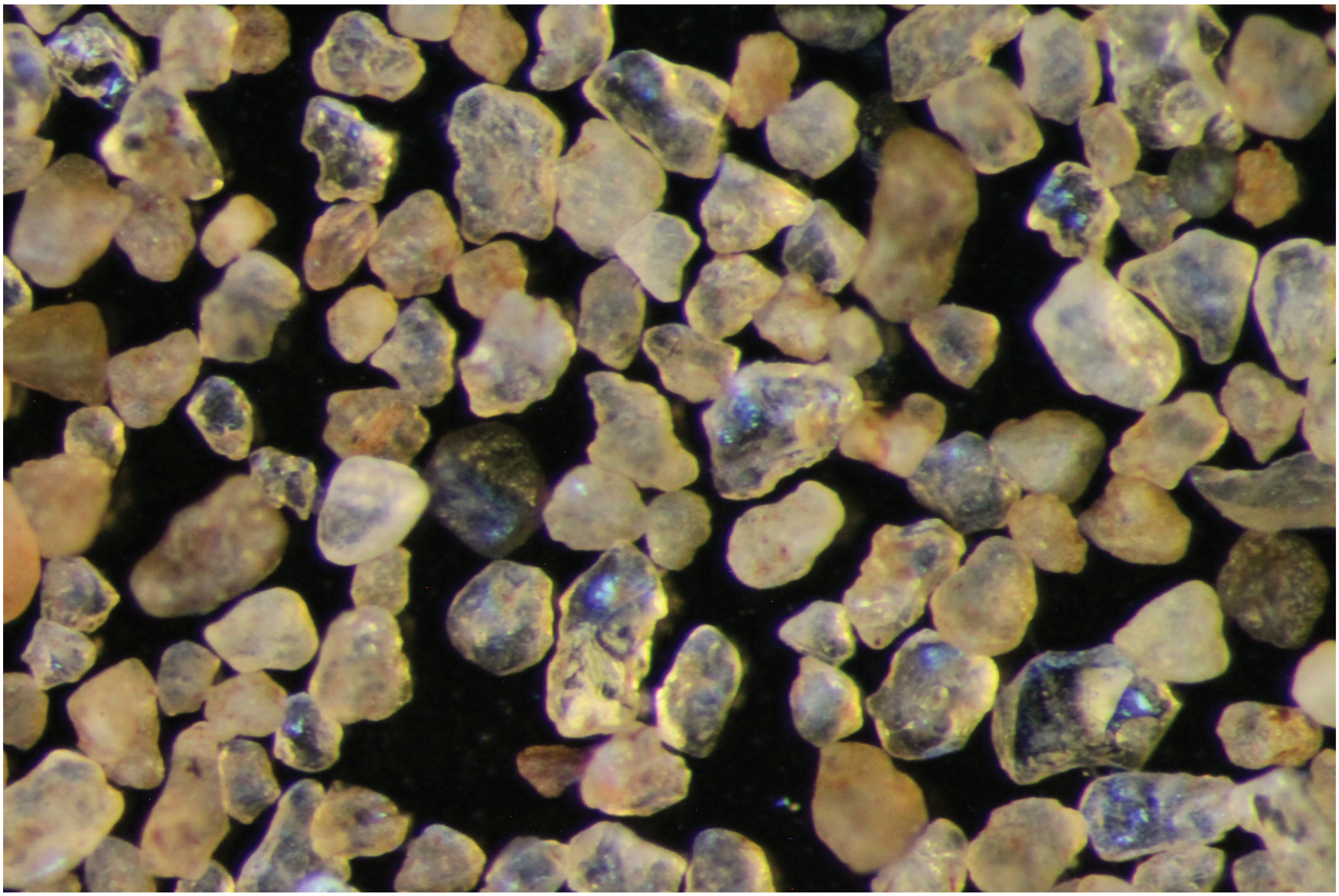
SNAP: A SURVEY OF NATIVE PROPPANT RESOURCES WITHIN MONTANA



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Cover image: Microscopic view—eolian sand reworked from glacial deposits.

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ABSTRACT

This report presents a characterization of sandstone formations throughout Montana for potential use as proppant applicable to hydraulic fracturing of oil and gas wells. A total of 351 samples from about 15 formations were collected and evaluated. Following sample preparation, most samples were evaluated for particle size distribution and quartz content. Additional tests were performed for sphericity, roundness, and crush strength.

The Tyler Formation showed the most promising results for proppant material based on laboratory tests that demonstrated the potential to withstand pressures of up to 8,000 psi. Twenty-one of the 34 samples collected met the minimum criteria for proppant, which is the highest percent of passing samples of any formation investigated in this study.

However, sandstone units within the Tyler Formation are generally thin, and this may limit its viability. Samples from the Quadrant Formation in the northeastern part of the Little Belt Mountains and in southwestern Montana near Dillon and Lima also met the minimum requirements for proppant. The Tensleep Formation shows potential within portions of a dune sandstone component that is interbedded with massive marine sandstones, particularly in Carbon County. Three units initially identified as target sandstones (Virgelle Formation, Fall River Formation, and Flood Member of the Blackleaf Formation) are unlikely to provide viable proppant. Data from this study are available on the Montana Bureau of Mines and Geology website: http://data.mbmg.mtech.edu/proppant/data.asp

INTRODUCTION

A joint project between academic units of Montana Tech and the Montana Bureau of Mines and Geology (MBMG) investigated the potential of Montana natural sands for use as proppant in hydraulic fracture stimulation. The MBMG staff oversaw field sampling and development of a publicly accessible database. Montana Tech students and staff conducted the laboratory analyses and generated the reports.

This 3-yr project, titled A Survey of Native Proppant Resources within Montana (SNaP), was funded by the Montana Board of Oil and Gas Conservation and was performed from 2013 through 2015. The goal of the project was to characterize sandstone formations throughout the State for potential use as proppant applicable to hydraulic fracturing of oil and gas wells.

A total of 351 samples were collected across the State (fig. 1). Not all of these samples are in the database, for reasons ranging from insufficient sample volume for testing, to sample contributions that were not sandstone. The database currently contains 321 separate sample records.

The SNaP public-access database, http://data.mbmg.mtech.edu/proppant/data.asp, from which figure 1 was generated, provides test results and pictures for each sample. The data presented include measurements from the API STD 19C standard (API, 2018): sphericity and roundness, particle size distribution, crush test results, sampled location, and the source formation. In addition, the SNaP dataset includes sandstone descriptions from measured sections obtained from geological publications, dissertations, and theses (appendix C and http://data.mbmg.mtech.edu/proppant/Data.asp?pageview=MS&).

Note: The procedures developed for the evaluation of exploratory material used in this project were based on the original API Recommended Practice 19C, 2008. Subsequent to the conclusion of this SNaP effort, the API has approved and published an updated version, now called STD 19C, with an errata published in 2020 (API, 2018). It is possible that some inconsistencies in SNaP procedures may be found when compared to the new test protocols laid out in their more recent standard.

Background

Hydraulic fracture stimulation utilizes a slurry of water, proppant, and small amounts of chemicals pumped at high pressures and flow rates into oil or gas reservoir rock deep underground. The process creates narrow fractures in the rock, increasing the surface area available for production of hydrocarbons by many orders of magnitude. Fracture stimulation and

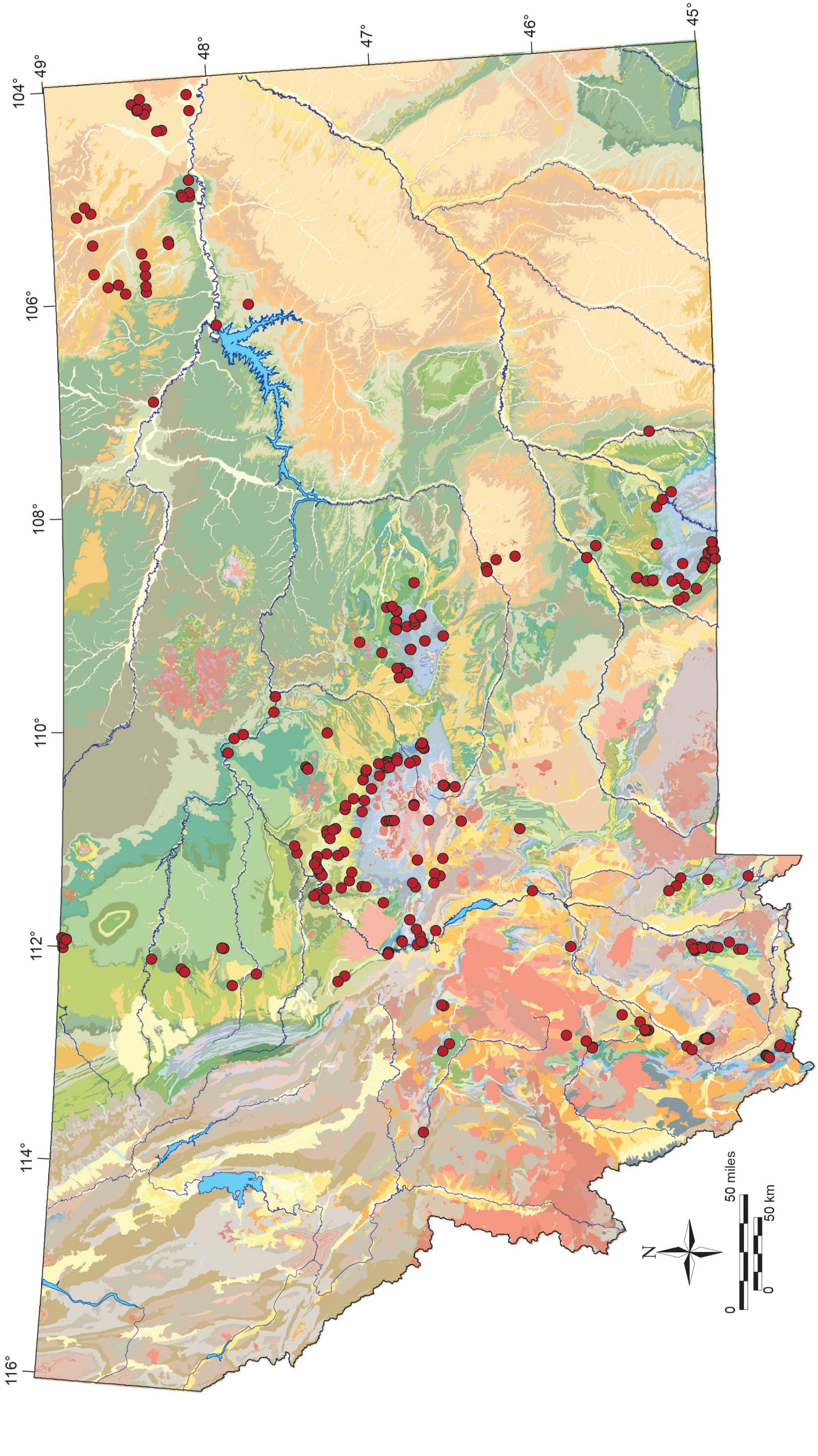


Figure 1. All tested samples plotted on a geologic map of Montana. An interactive version of this map is available in the SNaP database (http://data.mbmg.mtech.edu/proppant/Data.asp).

advances in directional drilling have made production from "unconventional" shale and tight sand reservoirs economically viable.

Proppant is a sand or sand-like material, either natural or manmade. Its purpose is to "prop" open the hydraulically induced fractures, preventing them from closing. At the end of the stimulation process, the liquid portion of the slurry is pumped back to the surface for disposal, while the proppant remains in the fractured reservoir rock. This propped fracture provides a high-conductivity pathway for the hydrocarbons to flow out of the reservoir rock, into the wellbore, and ultimately to the surface.

Proppant left in the fractures experiences long-term exposure to extreme conditions, including high cyclic stress and high temperatures. For this reason, the material must exhibit high strength and low solubility. High-purity silica sand is, by a wide margin, the most common and cost-efficient solution. However, purity of the material is only one of the parameters that define viable proppant. The proppant pack should be strong yet have internal voids sufficient to maintain high conductivity for the formation fluid. Because of the extreme environment, the sand grains must have a low number of internal crystalline defects and must be well-rounded. Angular material exhibits lower strength due to high point-loading, and lower conductivity (lower production) due to decreased pore space between the proppant grains.

LABORATORY METHODS

API STD 19C

The American Petroleum Institute (API) has adopted and published a set of standards designed to provide the oil and gas industry with the ability to predict the performance of material used as proppant. The API Recommended Practice 19C (STD 19C; API, 2018) specifies a number of proppant characteristics that are used for this purpose. These standards were previously also published by the International Organization for Standardization (ISO) as ISO 13503-2.

STD 19C was written to evaluate material that is marketed as proppant. It provides procedures for sampling of bulk and bagged material, methods to assess silt- and clay-size particle content, acid solubility, and loss of mass on ignition. These procedures are useful for, and perhaps even critical to, post-manufacturing evaluation.

However, the STD 19C methods do not describe procedures that are most important to exploration-stage evaluation of native materials. For the purposes of this study, the API procedures were used as a basis to inform methods of evaluating raw material for use as a proppant. The methods chosen for this evaluation are shown graphically in figure 2 and described below in the sequence that they were applied in the lab.

Processing for Disaggregation

Most of the samples collected for this study exhibited some degree of cementation of the mineral grains. In order to be useful as a proppant, the material has to be disaggregated, separating the individual grains. In the lab, this process primarily involved crushing the material by hand using a clean mortar and pestle. In some cases, a jaw crusher was used to reduce the material to a manageable size prior to further processing with the mortar and pestle.

Weigh, Wash, Dry, and Weigh

The bulk disaggregated sample was weighed to provide a baseline. The sample was then washed with flow rate sufficient to float off material that was smaller than about 200 mesh (~75 µm). Generally, water was used for this process. Samples with calcareous cement were subjected to a mild hydrochloric acid wash to assist in providing a clean sample.

The sample was then dried in a laboratory oven for a minimum of 24 h at 95ºC and reweighed. The loss in mass from the bulk sample, to the washed and dried end point, allowed an estimate of the percentage of silt-size and smaller particles that were present in the bulk sample. This result may be useful in predicting requirements for a fugitive dust control program or estimating waste.

Bulk Particle Size and the "Exploratory Stack"

The STD 19C defines a set of particle size distributions, or designations, that are widely used in the oil and gas industry. Table 1, taken from the STD 19C, indicates the sieve stack that is used for each of these size designations. The table also identifies the first and second primary sieves in each of these ranges using bold type face. The standards state that 90% or more of the material must be smaller than the first primary and bigger than the second. Put another way, no more than a total of 10% of the particles in a commercial 20/40 material may be larger than 20 mesh (the first primary) and smaller than the second primary, 40 mesh.

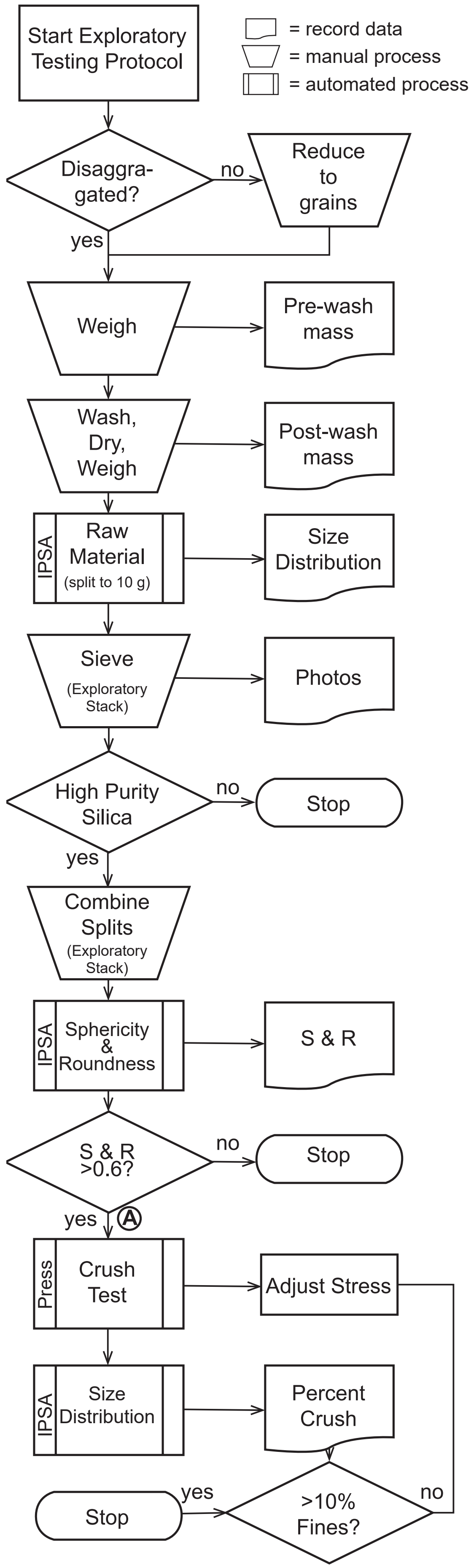


Figure 2. Flow chart of the lab testing protocol.

A key measurement in this study was the fraction of the material that fell into each of the standard API size designations. This information is useful for predicting the fractions of usable product and the amount of waste that might be generated during processing of the material as it is prepared for sale. The size distribution information was used in this study to determine the dominant size fraction, which was then separated out as the target for the remaining tests.

The SNaP protocol was designed around an "exploratory sieve stack" consisting of eight ASTM sieves—numbers 16, 20, 30, 40, 50, 60, 70 and 140—plus a pan. This selection of sieves permits, in one operation, the separation of the material so that the dominant API size fraction can be assembled. The first column in table 2 lists the API size designations. The second column indicates the sieves in the exploratory stack whose material is combined to create that API size fraction.

A Horiba CAMSIZER XT imaging particle size analyzer (IPSA) was used to provide a distribution of particle sizes present in the sample that is essentially continuous. The CAMSIZER report was set up to list the fraction of material that would fall into each of the sieves in the exploratory stack. These results were then used to determine which of the API designations would contain the dominant fraction of the raw material, by simply adding together the fractions binned in each of the exploratory sieves by the IPSA. Figure 3 shows a CAMSIZER report and associated information.

Sieve to Separate by Size

In this step, the bulk sample was sieved for 10 min at an amplitude of 0.99 mm, using the exploratory stack on a Retsch AS-200 Control vibratory sieve shaker. Elements of the STD 19C standard such as roundness, sphericity, and crush resistance were conducted only on the dominant size fraction as determined from the IPSA, based on the assumption that it is most likely to be of economic interest to developers.

Micrographs and Mineralogy

A sample from each of the sieve sizes in the exploratory stack was photographed using a Nikon SMZ800 microscope with a Canon EOS Rebel T1i camera. In many of the photographs, a 0.5-mm pencil lead provided a size reference. These images are available via the website for the SNaP project, at http://data.mbmg.mtech.edu/proppant/data.asp.

Table 1—ASTM Test Sieve Sizes

Sieve-opening Sizes μm											
	3350/ 1700	2360/ 1180	1700/ 1000	1700/ 850	1180/ 850	1180/ 600	850/ 425	600/ 300	425/ 250	425/ 212	212/ 106
Typical Proppant/Gravel-pack Size Designations											
	6/12	8/16	12/18	12/20	16/20	16/30	20/40	30/50	40/60	40/70	70/140
Stack of ASTM Sieves [a,b]											
Upper designating sieve in bold type	4	6	8	8	12	12	16	20	30	30	50
	6	**8**	**12**	**12**	**16**	**16**	**20**	**30**	**40**	**40**	**70**
	8	10	14	14	18	18	25	35	45	45	80
Lower designating sieve in bold type	10	12	16	16	**20**	20	30	40	50	50	100
	12	14	**18**	18	25	25	35	45	**60**	60	120
	14	**16**	20	**20**	30	**30**	**40**	**50**	70	**70**	**140**
	16	20	30	30	40	40	50	70	100	100	200
	pan	pan	pan	pan	pan	pan	pan	pan	pan	pan	pan

[a] Sieve series as defined in ASTM E11 (U.S. Alternative designation); refer to Annex A for opening size in μm.

[b] Test sieve stacked in order from top to bottom, largest opening on top.

Table reproduced from table 1, API STD 19C, 2nd Edition, 2018, courtesy of the American Petroleum Institute.

Table 2. Exploratory stack and API size designation.

API Size	Sieve Contents Used
16/20	20
16/30	20, 30
20/40	30, 40
30/50	40, 50
40/60	50, 60
40/70	50, 60, 70
70/140	140

The microscopic investigation was used to estimate the percentage of non-quartz particles in the sample and, qualitatively, the crystalline structure of the quartz present in the sample. The optical clarity of the individual grains is indicative of mono-crystalline quartz, which tends to have a greater resistance to crush. If a large fraction of the material appeared to consist of feldspars or other non-quartz minerals, testing was stopped and the sample marked as not meeting API minimum standards.

Although there is no guidance from the STD 19C on what fraction of non-silica material can be tolerated, our laboratory experience with economically viable commercial proppant is that it is generally quite homogenous. Sand with 99% silica content generally demands a premium price.

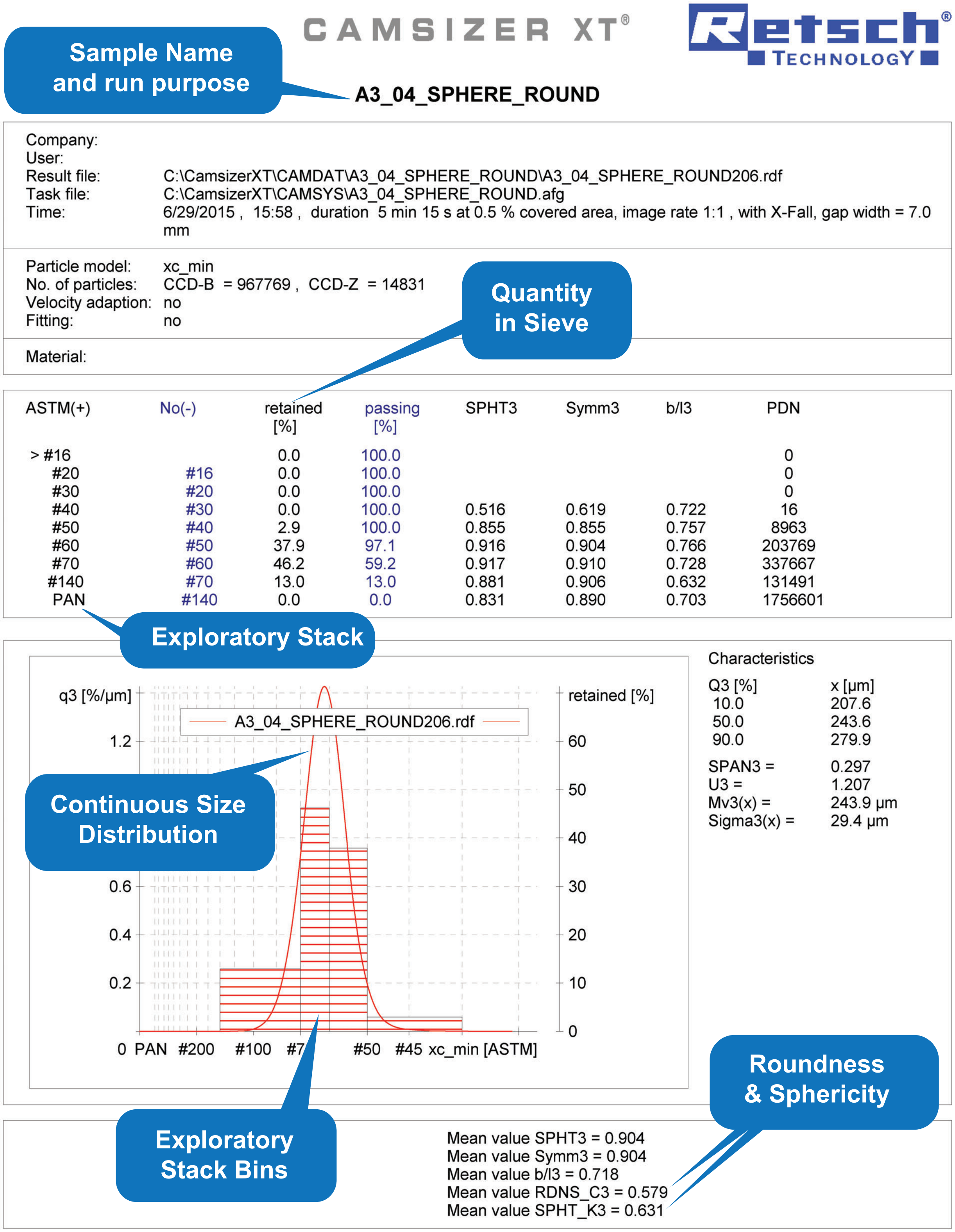
Microscopic investigation was also used to identify grain clusters—two or more mechanically attached (cemented) neighboring grains. High-quality proppant contains very few clusters, because they produce inaccurate particle sizes, and release fines when the generally weakly bound cement fails.

Combine Splits to Create Dominant API Size

The dominant API size fraction that was calculated in the step Bulk Particle Size and Exploratory Stack was used to identify which sieve contents must be combined to produce the dominant API size designation used for further testing in this protocol. For example, a dominant size fraction of 40/70 indicates that material in sieves 50, 60, and 70 was combined at the end of the sieving process. The material retained in the sieves that was not part of this largest fraction was retained separately.

Sphericity and Roundness

A riffle sample splitter (Humboldt Micro Riffle Splitter Model #H-3971C) was used to collect a 10-g aliquot split-sample from the dominant API size frac-



Company:	
User:	
Result file:	C:\CamsizerXT\CAMDAT\A3_04_SPHERE_ROUND\A3_04_SPHERE_ROUND206.rdf
Task file:	C:\CamsizerXT\CAMSYS\A3_04_SPHERE_ROUND.afg
Time:	6/29/2015 , 15:58 , duration 5 min 15 s at 0.5 % covered area, image rate 1:1 , with X-Fall, gap width = 7.0 mm
Particle model:	xc_min
No. of particles:	CCD-B = 967769 , CCD-Z = 14831
Velocity adaption:	no
Fitting:	no
Material:	

ASTM(+)	No(-)	retained [%]	passing [%]	SPHT3	Symm3	b/l3	PDN
> #16		0.0	100.0				0
#20	#16	0.0	100.0				0
#30	#20	0.0	100.0				0
#40	#30	0.0	100.0	0.516	0.619	0.722	16
#50	#40	2.9	100.0	0.855	0.855	0.757	8963
#60	#50	37.9	97.1	0.916	0.904	0.766	203769
#70	#60	46.2	59.2	0.917	0.910	0.728	337667
#140	#70	13.0	13.0	0.881	0.906	0.632	131491
PAN	#140	0.0	0.0	0.831	0.890	0.703	1756601

Characteristics

Q3 [%]	x [µm]
10.0	207.6
50.0	243.6
90.0	279.9

SPAN3 = 0.297
U3 = 1.207
Mv3(x) = 243.9 µm
Sigma3(x) = 29.4 µm

Mean value SPHT3 = 0.904
Mean value Symm3 = 0.904
Mean value b/l3 = 0.718
Mean value RDNS_C3 = 0.579
Mean value SPHT_K3 = 0.631

Figure 3. Example CAMSIZER IPSA report. Annotations identify some of the information used in sample evaluation.

tion subsample for remeasurement with the IPSA.

This measurement served two purposes. The first was to confirm that the separation process produced a sample of the correct size. The STD 19C criteria were used for this determination, which states that no more than 10% of the material may fall outside of the sizes specified by the first and second primary sieves[1].

The second purpose was to measure the sphericity and roundness of the largest size fraction. Both sphericity and roundness must exceed 0.6 to qualify for continued testing. If either of these shape results did not meet this API threshold, the sample was identified as having failed, and testing was stopped.

The API standard procedure for sphericity and roundness states that 20 particles should be isolated from the bulk, and each assigned a value for roundness and sphericity by comparing them to the Krumbein/Sloss (API STD 19C) chart (fig. 4). For this study, the calculations of sphericity and roundness provided by the IPSA were used, since this speeds the process and avoids the human bias associated with the API method.

[1]API STD 19C defines the "proppant size designation" by the first and last sieve in the sieve stack, referred to as the "first and second primary sieves," not including the larger pre-sieve. The standard states that not more than 0.1% of the material may be retained by the larger pre-sieve and no more than 1% may pass the second primary into the pan.

Crush Test

The "k factor" assigned to a proppant is defined in the STD 19C protocol as the highest crush stress, in thousands of pounds per square inch (psi), that produces a fraction of fines (by weight) of less than 10%. The percentage of "fines" is defined as the fraction of the material that passes the second primary sieve. For the SNaP study, the post-crush IPSA run was used to determine the percentage of fines.

If the measured sphericity and roundness of the selected size fraction approached or exceeded the standard of 0.6, it was then split to produce an aliquot of 40 g, loaded into a crush cell (specified in STD 19C), and exposed to a stress of 6,000 psi, per the methods of section 11 of STD 19C. The entire 40-g sample was subsequently tested again with the IPSA to determine the change in the particle size distribution.

If the percentage of fines was greater than 10%, a fresh 40-g aliquot was split from the largest API size fraction and retested at 5,000 psi. This material was then tested for size distribution using the IPSA and the

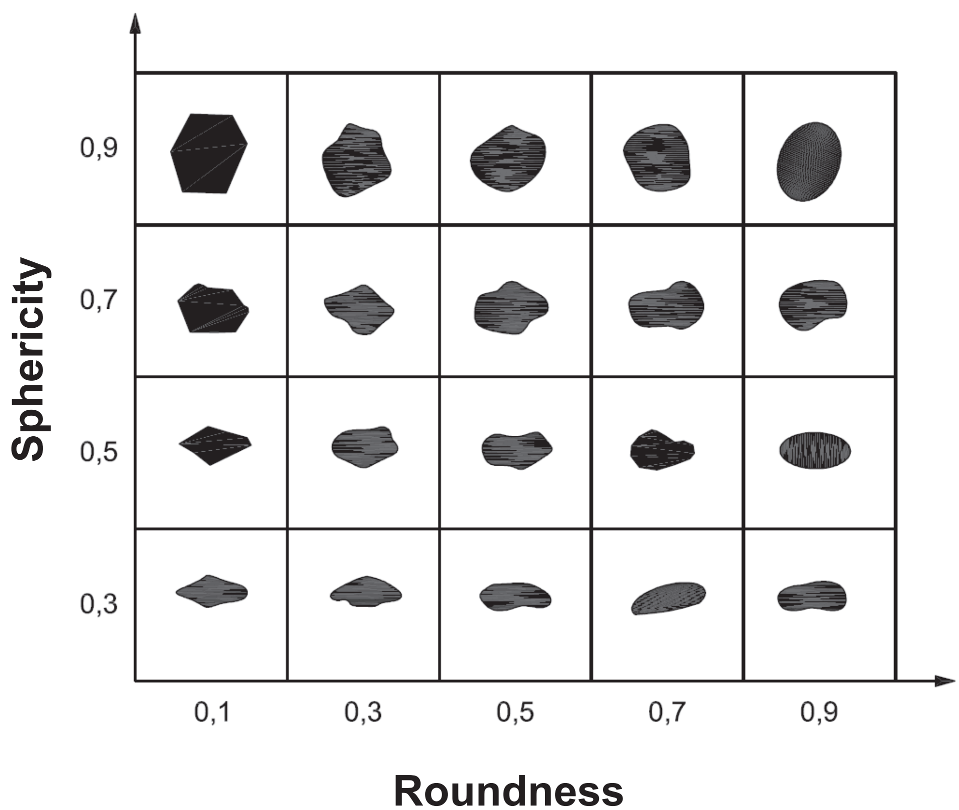


Figure 4. Chart used for calculation of sphericity and roundness, reproduced from figure 5, API STD 19C, 2nd Edition, 2018, courtesy of the American Petroleum Institute.

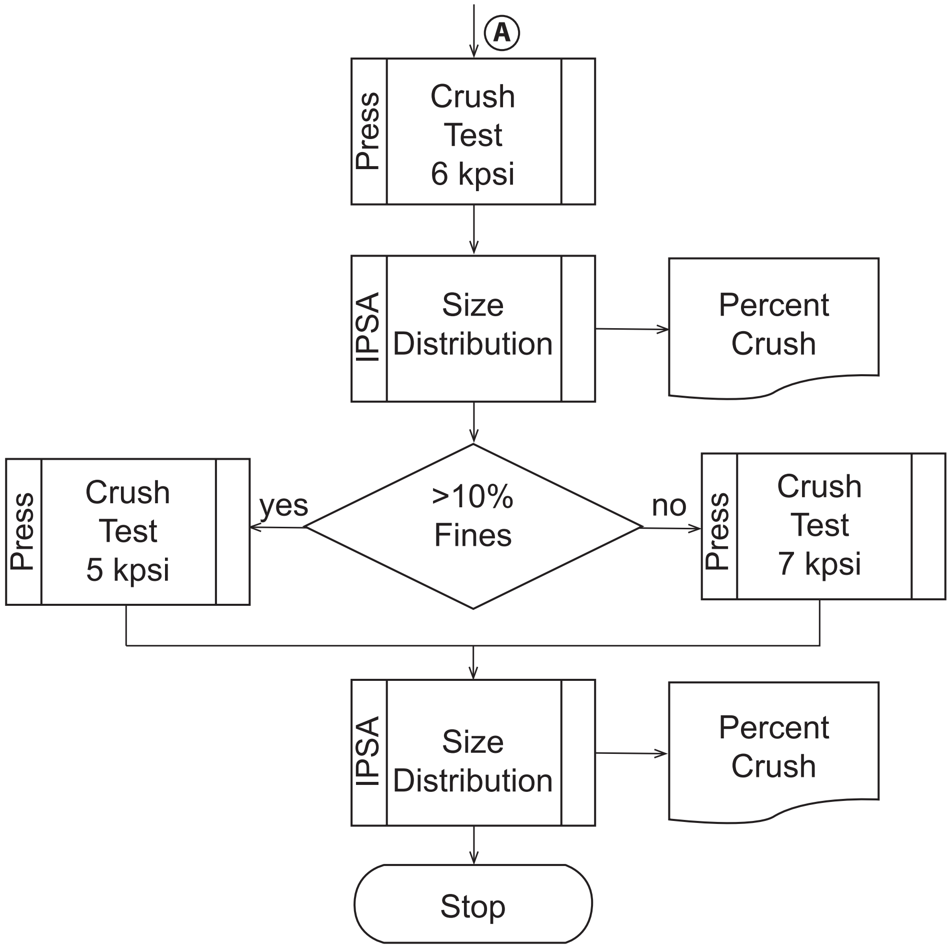


Figure 5. Specific crush stress protocol used for SNaP.

percentage of fines reported in the database.

If the percentage of fines produced at 6,000 psi was less than the 10% threshold, the material was re-tested at 7,000 psi (fig. 5). Not all samples that passed at one closure stress were tested to the point of failure.

The crush testing protocol that was developed for and used in the SNaP project is summarized in the flow chart of figure 2. Figure 5 provides specifics of the decision tree used for selecting crush stress values, as described above. This testing flow replaces the portion in figure 2 at the point labeled Ⓐ. This portion of the flow chart was used in the SNaP project to provide additional information on the samples. In an exploratory program that uses only one crush test point to identify samples for future investigation, the more time-consuming method of figure 5 may not be practical.

Industry data show that the smaller API size designations of a material consistently demonstrate greater strength (Aou and others, 2016). Because most of the material in this study was at smaller sizes (for example, 40/70 and 70/140 fractions), efficiency gains were realized by starting the crush tests at 6,000 psi.

FIELD SAMPLING APPROACH

The primary criteria for determining which sandstones to sample were the abundance of quartz, presence of rounded and spherical sand grains, and friability of the bulk rock. High-energy marine deposits and marginal marine sand dune (eolian) deposits were considered the most likely possibilities for quartzose sandstone with well-rounded and spherical grains. The following sandstones were initially identified as sampling targets, with the understanding that facies changes likely produced compositional and textural variability, and that friability may be highly variable:

- Virgelle Formation (Cretaceous),
- Fall River Formation (Cretaceous),
- Flood Member of Blackleaf Formation (Cretaceous),
- Basal sandstone of the Thermopolis Formation

(Flood Member and Fall River equivalent; Cretaceous),
- Greybull Member of the Kootenai Formation (Cretaceous),
- Sunburst Member of the Kootenai Formation (Cretaceous),
- Quadrant Formation (Pennsylvanian),
- Tensleep Formation (Pennsylvanian), and
- Tyler Formation (Pennsylvanian and Mississippian).

In addition, the Goose Egg Formation (Permian) was considered a possible sampling target but was not sampled because of poor-quality outcrops in its limited area of exposure in Montana.

Initially, the Flathead Formation (Cambrian) was not included as a sampling target because of tight cementation, but it was added with the discovery during field sampling of friable Flathead in central Montana. Kibbey Formation (Mississippian) was not initially included because of its expected very fine grain size, but was added when outcrops were found with suitable grain size. The Shedhorn Formation (Permian) was also added based on field examination in the Gravelly and Madison Ranges. A report describing Quaternary eolian deposits (unconsolidated dune sand) suitable for proppant (Hickin and others, 2010) prompted sampling of extensive Quaternary eolian deposits reworked from glacial deposits in northeastern Montana. In this area, low transportation costs could make discovery of viable proppant material economically attractive. An unrelated eolian deposit was also sampled along the Missouri River near Ulm in central Montana. All of the targeted sandstone and sand deposits produced at least one sample that met the API minimum criteria for proppant except three: Virgelle Formation, Flood Member of the Blackleaf Formation, and Fall River Formation.

Other sandstones contained large fractions of non-quartz clasts and therefore were not included in the initial sampling target list. Nevertheless, some formations not initially identified—or those with less-than-ideal characteristics—were sampled and tested in order to provide more comprehensive results. The additional sandstones sampled include:

- Tongue River Member of the Fort Union Formation (Tertiary),
- Hell Creek Formation (Cretaceous),
- Fox Hills Formation (Cretaceous),
- Judith River Formation (Cretaceous),
- Eagle Formation (Cretaceous),
- Frontier Formation (Cretaceous),
- Terrestrial sandstone from the Kootenai Formation (Cretaceous), and
- Morrison Formation (Jurassic).

Efficacy of the sampling program benefited from first-hand knowledge of the stratigraphic units and outcrop locations by MBMG geologists who had previously mapped much of the sample area. If available, geologic field notes and large-scale geologic field maps prepared by the MBMG geologists were used to locate outcrops. U.S. Geological Survey geologic and topographic maps were also utilized.

Measured section descriptions from published sources, dissertations, and theses were compiled and used to locate additional sandstone for sampling. Information from these historical sources along with researchers' notes specific to the interests of the SNaP project are shown in appendix C. These sources were also used to rule out proppant potential of sandstones in certain areas. For example, the poorly accessible Flathead Formation in the Bighorn Mountains was described as tightly cemented, and therefore was not sampled.

Field Protocol

Data collected in the field included the latitude, longitude, and elevation as measured with a handheld GPS. Samplers were requested to provide pictures of the sampling location and outcrop. Approximately 0.5 kg of material was collected at each point and placed into a plastic or cloth sack with tight weave to reduce the loss of fines during transportation to the lab at Montana Tech. A field sampling form was provided for the required information (appendix B). Some microscopic images were acquired in the MBMG Billings office using an OMANO OM99 microscope with an Optix Summit Series camera.

Most samples were collected along roads, but some involved walking less than a half mile in order to access the sandstone. Grab samples were taken of sand/sandstone that, based on field examination, appeared likely to meet the proppant criteria. In some cases, more than one sample was taken from different stratigraphic horizons at the same sample location. The Quadrant and Flathead Formations were sampled even where they appeared tightly cemented to help delineate the area where friable sandstone is present in those formations.

RESULTS

Descriptions of field observations and summaries of the lab test results are presented below. Formations that showed potential for proppant source are presented first and are followed by descriptions of formations that did not yield positive results.

Formations with Potential as a Proppant Source

Eolian (Quaternary)

Twenty-eight samples were collected from Quaternary eolian deposits reworked from glacial sediment in Valley, Roosevelt, Sheridan, and Daniels Counties in northeastern Montana (fig. 6A). Another eolian deposit was sampled (GFS 22, fig. 6B) in Cascade County just south of Ulm along the west bank of the Missouri River.

Most of the samples did not pass the lab tests because of an insufficient percentage of quartz grains.

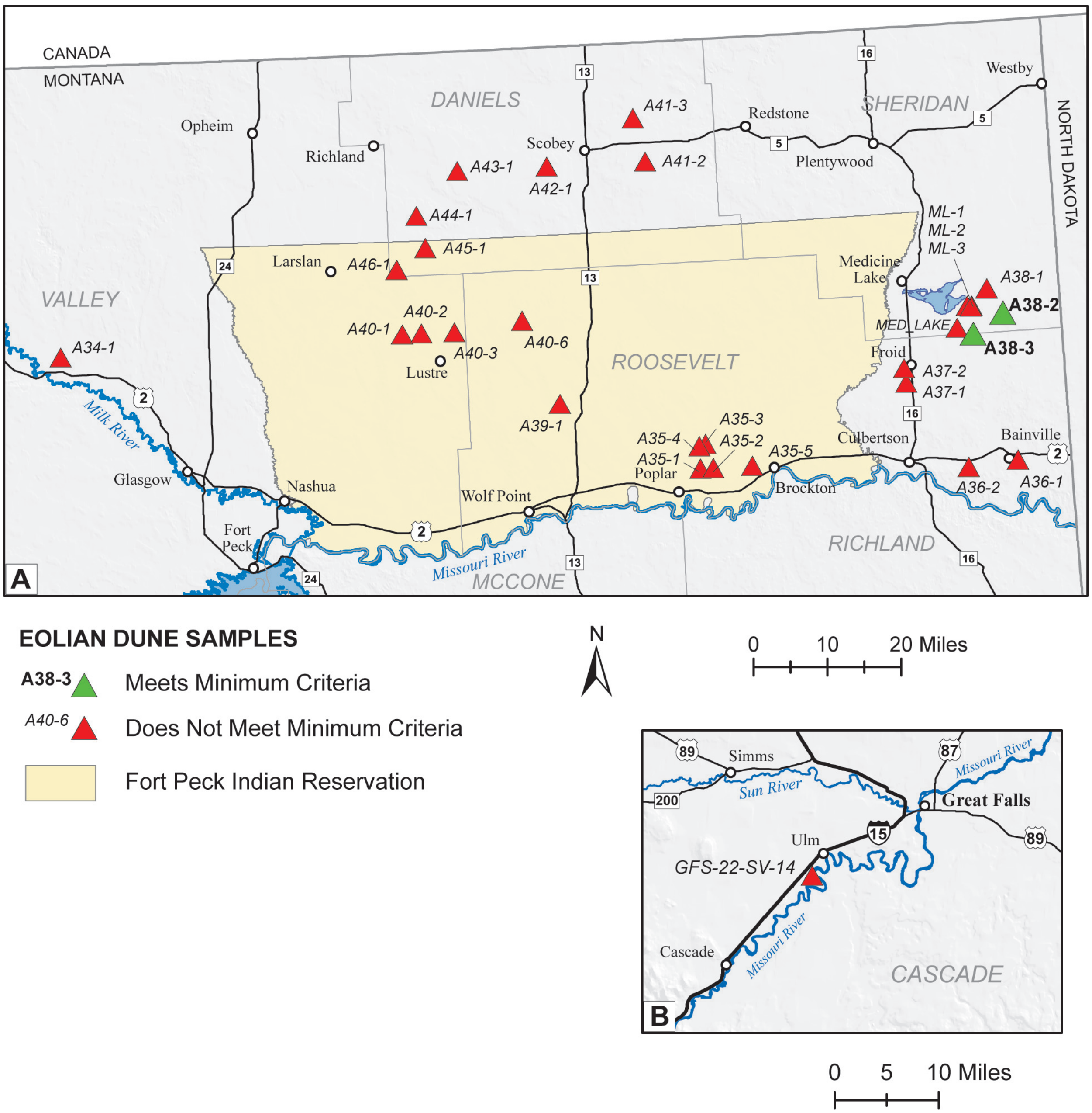


Figure 6. Sample locations—eolian deposits (sand dunes). (A) Location of eolian deposits reworked from glacial sediment. Two samples in the eastern extent of samples, identified by green icons and bold font, passed the minimum requirements for proppant. (B) Location of an eolian deposit sample from west-central Montana.

Two samples, A38-2 and A38-3, collected from the southeastern part of Sheridan County, in the eastern part of the sampling area, passed all tests except the highest crush test. These both had mesh size of 70/140 and passed the 5,000 psi crush tests at 9.3% and 7.7% fines produced, respectively.

Figure 7 compares the quality of the sand from sample A38-3 (passed testing) with that of sample A43-1 (failed testing). The clarity and relative abundance of quartz grains were higher in sample A38-3.

GFS-22 (fig. 6) had an API sieve size of 40/70; however, upon inspection with an optical microscope, it appeared that the sample contained significant amounts of non-quartzose material and was therefore less desirable for use as proppant. The sphericity and roundness of this sample were 0.573 and 0.525, which also failed to meet the minimum requirements for further testing. Figure 8 shows an example of the 70 mesh material from sample GFS-22 with several lithic clasts identified.

Table 3 summarizes the results for those eolian sand samples that met the minimum API criteria for proppant. As stated above, in order to meet the API specifications a sample must consist mainly of quartz sand, have sphericity and roundness values exceeding 0.6 (or nearly so), and produce 10% or less fines at a minimum crush stress of 5,000 psi.

Thermopolis Formation basal sandstone (Cretaceous)

Nine samples were collected from the basal sand-

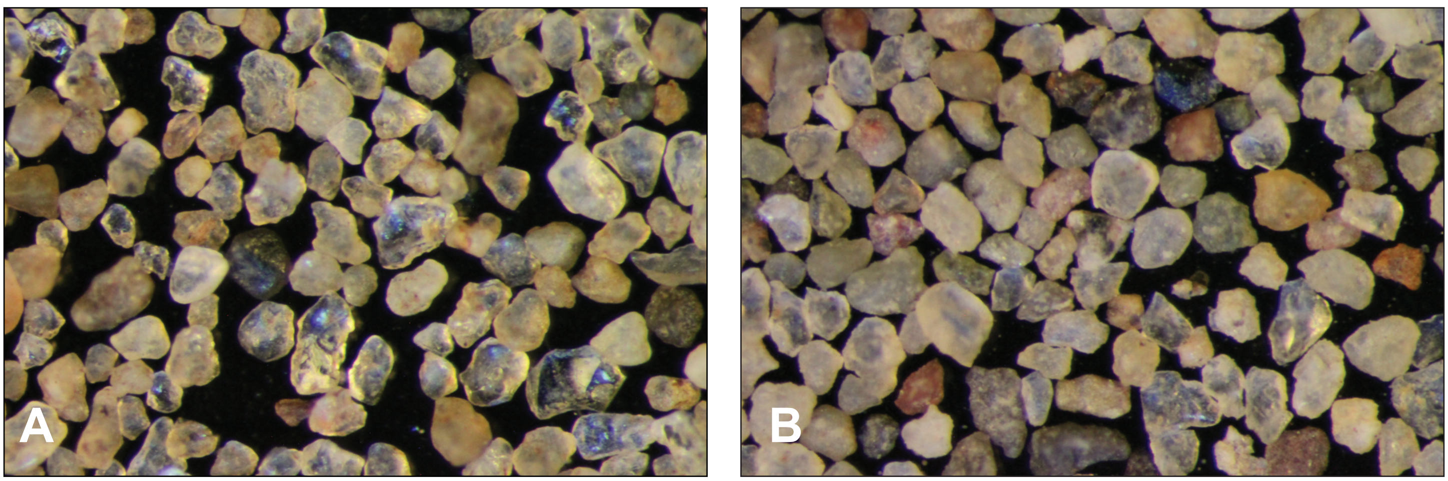


Figure 7. Microscopic view—eolian sand reworked from glacial deposits. (A) Sample A38-3 at 70/140 mesh size (passed). (B) Sample A43-1 at 70/140 mesh size (failed).

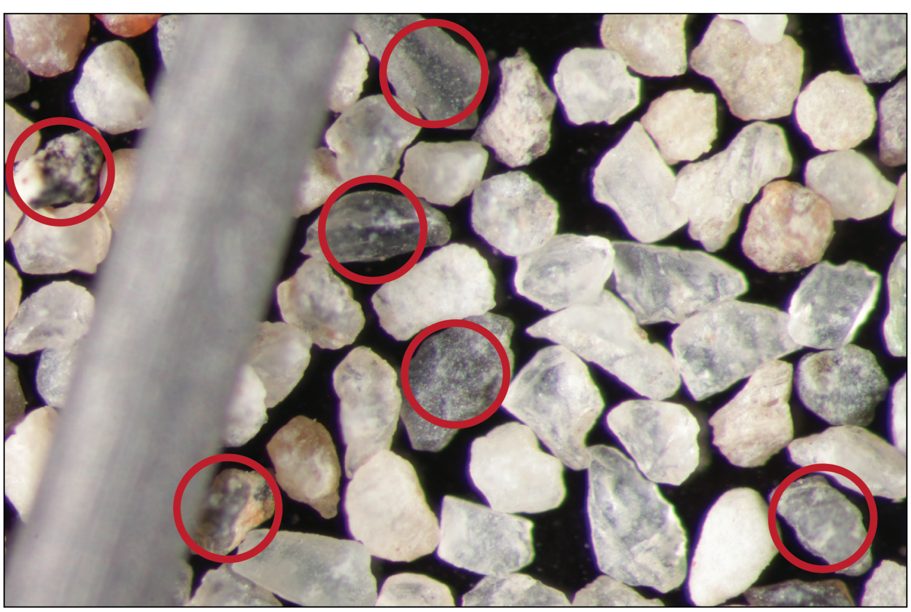


Figure 8. Microscopic view—eolian deposit near Ulm, Sample GFS-22. 70 mesh shown. Pencil lead (0.5 mm wide) for scale. The red circles identify some of the lithic clasts that hinder the use of this eolian sand as proppant.

Table 3. Eolian deposit (Quaternary) samples that met the minimum criteria for proppant.

Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	6,000 psi	7,000 psi	8,000 psi
A38-2	48.42565	-104.21662	SHERIDAN	70/140	0.622	0.659	9.3	10.1		
A38-3	48.38948	-104.30852	SHERIDAN	70/140	0.618	0.659	7.7	12.0		

Note. Both of the samples had adequate sphericity and roundness values as observed using the imaging particle size analyzer (IPSA). Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

stone of the Thermopolis Formation, three of which passed the minimum API standards requirements for proppant (fig. 9).

Of the nine samples collected from the Thermopolis Formation basal sandstone, all but ENN-16 had most sand grains collect in the 140 sieve size. Most ENN-16 sample grains collected in the 16/30 API mesh size; however, these grains showed extensive clustering, indicating inadequate disaggregation.

The samples that met minimum API standards for proppant were HL-03, ENN-14, and RING-01. HL-03 and RING-01 passed crush testing at 6,000 psi with only 4.5% and 7.4% fines produced and then failed crush tests at 7,000 psi (10.6% and 10.7%, respectively). ENN-14 failed the crush test at 6,000 psi (12.5% fines produced), and then passed the crush test at 5,000 psi with 8.8% fines produced.

Samples collected from adjacent locations within the basal sandstone of the Thermopolis Formation are compared in figure 10. Grains from sample ENN-14 (fig. 10A) exhibit lower sphericity and roundness than those from sample ENN-15 (fig. 10B). However, ENN-15 failed crush tests and ENN-14 passed. Samples HL-03 and HL-04 (fig. 10C, 10D) display different degrees of sand grain roundness. Sample HL-03 passed the crush test at 5,000 psi (4.5% fines) but failed at 6,000 psi (10.6% fines.) Table 4 summarizes the results for Thermopolis Formation basal sandstone samples that met the minimum API criteria for proppant.

All other samples failed to meet minimum criteria for proppant due to insufficient roundness. ENN-15 passed all preliminary tests but failed the crush tests at 6,000 psi and 5,000 psi with 15.9% and 11.4% fines produced, respectively. Overall, test results indicate that the basal sandstone of the Thermopolis Formation may provide marginally viable proppant material.

Kootenai Formation (Cretaceous)

The Kootenai Formation is a non-marine deposit throughout Montana with two marginal marine exceptions: the Sunburst member (informal stratigraphic unit) in the middle Kootenai Formation near Great Falls, and the Greybull Member in the uppermost part of the Kootenai Formation in south-central Montana. The non-marine sandstones were initially not sample targets because they typically contain abundant chert and lithic clasts, whereas the Sunburst and Greybull Members were targeted, because those sandstones are highly quartzose.

Kootenai Formation: Greybull Member

Ten samples were collected from the Greybull Member of the Kootenai Formation, which is only exposed in the Pryor Mountains in Yellowstone and Carbon Counties (fig. 11). Table 5 summarizes the results for Greybull Member samples that met the minimum API criteria for proppant.

Samples A03-2 and A03-3 passed the proppant test criteria, including crush testing at 5,000 psi that produced 5.0% and 6.7% fines, respectively. Each sample had 40/70 first and second primaries and exhibited strong sphericity and roundness. Sample A31-1 also passed the proppant criteria with 8.6% fines produced after the 6,000 psi crush test. The remaining samples failed the crush test at 5,000 psi. Sample A31-1 was collected from above a fluvial channel and sample A31-2 was taken 20 ft below the channel at the same latitude and longitude; the sand grains from the lower sample exhibited much lower roundness than those of the sample taken from above the channel.

Pictures of three mesh size fractions taken from three sieves, 40 mesh (30-/40+), 50 mesh (40-/50+), and 70 mesh (60-/70+) from sample A03-2 (fig. 12), indicate an abrupt change in particle size at the 40-/50+ boundary. This results from a large number of clusters in material taken from the 40 mesh sieve,

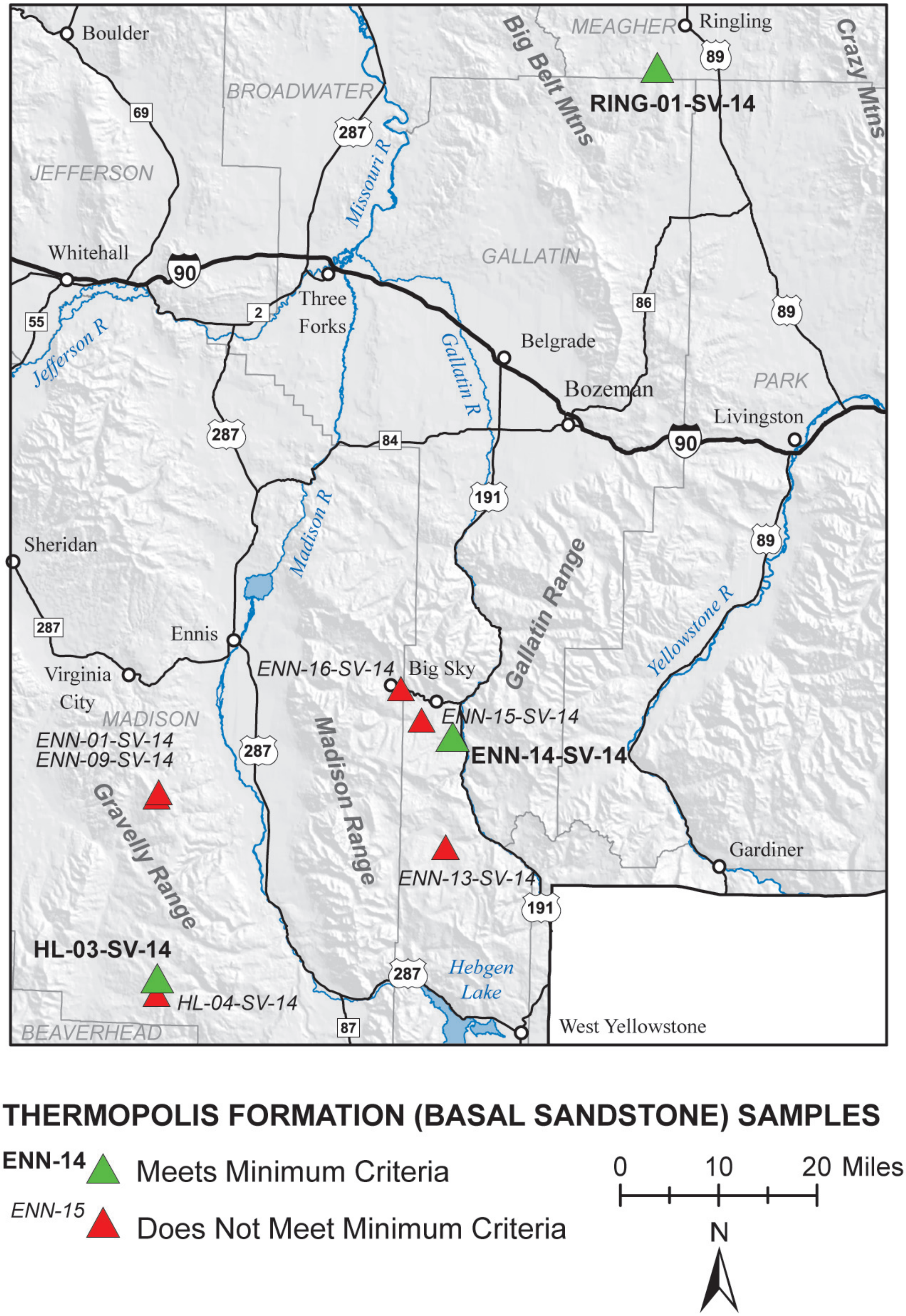


Figure 9. Sample locations—Thermopolis Formation basal sandstone, in Madison, Meagher, and Gallatin Counties, southwest Montana.

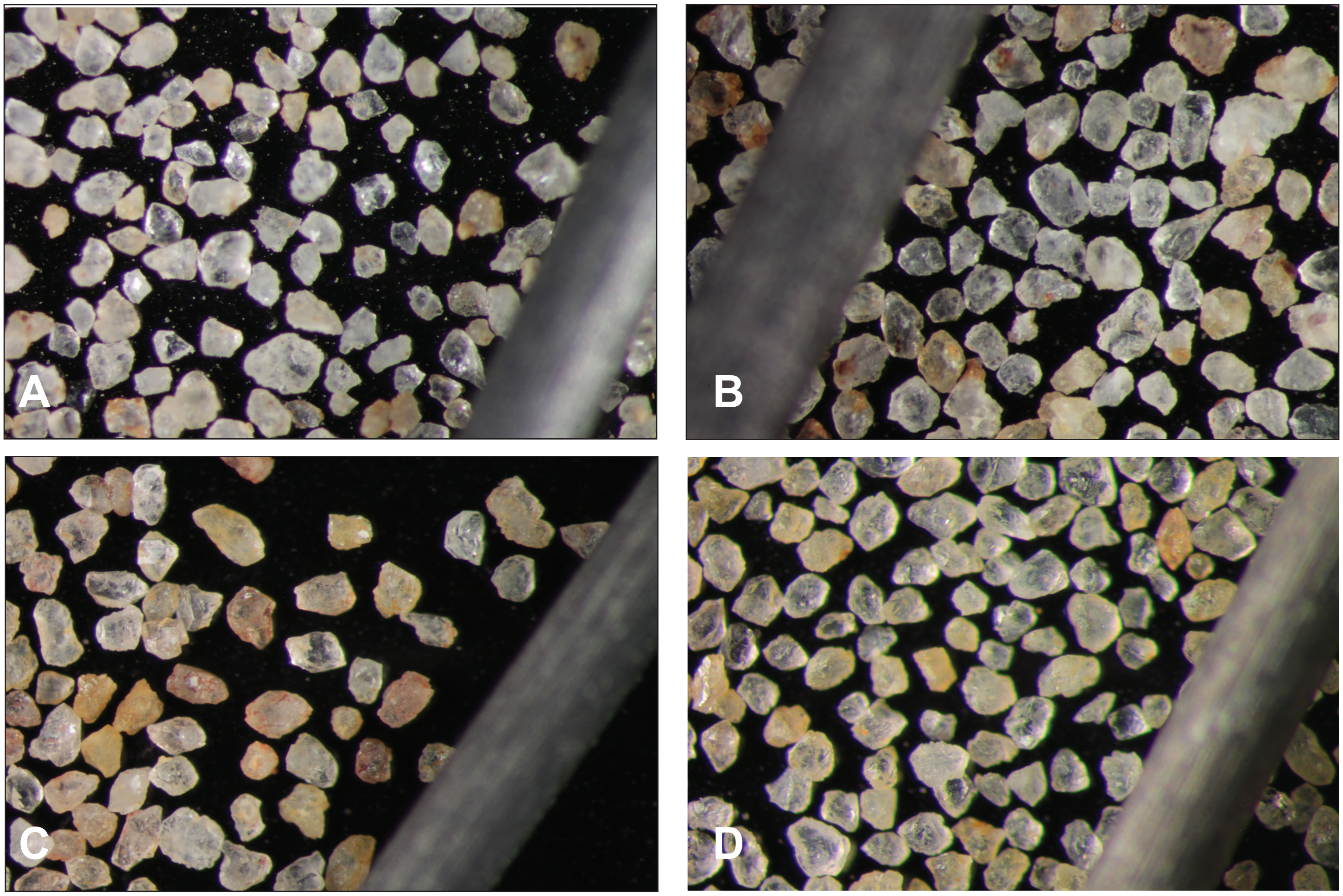


Figure 10. Microscopic view—Thermopolis Formation, basal sandstone. Comparison between the grains retained in the 140 sieve size from samples collected from adjacent locations, ENN-14 and ENN-15 (A and B), and HL-03 and HL-04 (C and D). Samples shown in A and C passed crush test; the sample shown in B failed crush tests. The sample shown in D did not exhibit sufficient roundness (0.424) for further testing. Pencil lead (0.5 mm wide) for scale.

Table 4. Thermopolis Formation, basal sandstone samples that met the minimum criteria for proppant.

							% Fines			
Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	5,000 psi	6,000 psi	7,000 psi	8,000 psi
ENN-14-SV-14	45.217170	-111.268165	GALLATIN	70/140	0.619	0.553	8.8	12.5		
HL-03-SV-14	44.850346	-111.869837	MADISON	70/140	0.655	0.655		4.5	10.6	
RING-01-SV-14	46.209226	-110.865616	MEAGHER	70/140	0.651	0.620		7.4	10.7	

Note. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

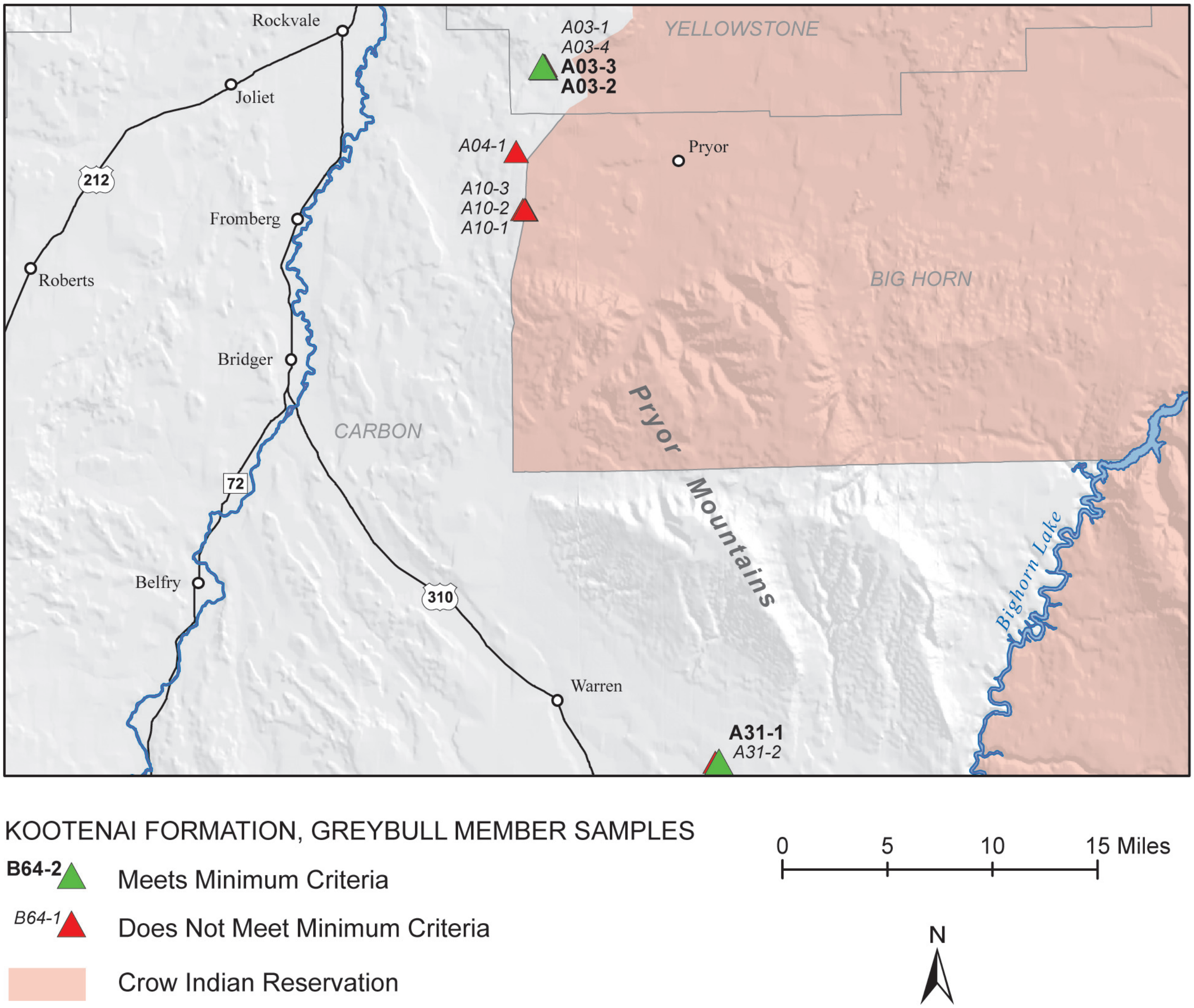


Figure 11. Sample locations—Kootenai Formation, Greybull Member, southeastern Montana.

Table 5. Kootenai Formation, Greybull Member samples that met the minimum criteria for proppant.

Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	% Fines 6,000 psi	% Fines 7,000 psi	% Fines 8,000 psi
A03-2	45.4962264	-108.6652333	CARBON	40/60	0.626	0.683	5.0	20.2		
A03-3	45.49671267	-108.6645065	CARBON	40/70	0.630	0.633	6.7	11.1		
A31-1	45.01635	-108.50602	CARBON	40/70	0.630	0.604		8.6	11.7	

Note. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

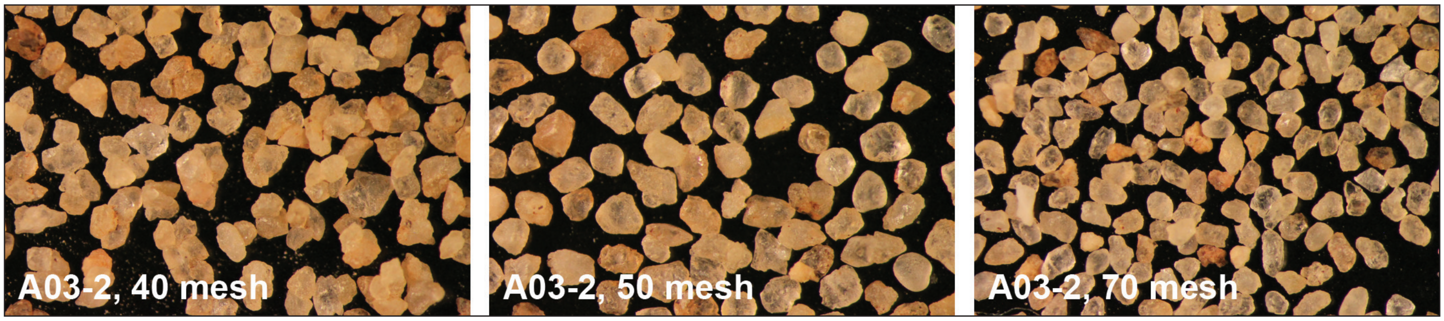


Figure 12. Microscopic view—Kootenai Formation, Greybull Member. Three size fractions from sample A03-2.

whereas there are no obvious clusters in either the 50 or 70 mesh fractions.

Kootenai Formation: Sunburst Member

Thirty samples were collected from the Sunburst member of the Kootenai Formation near Great Falls, Montana (fig. 13).

Eleven of the samples met the minimum API criteria for proppant. All but one of the passing samples (GFS-07) had API sizes of 70/140. GFS-07 performed notably well in tests, with an API sieve size of 40/70 and passed crush tests at 6,000 psi and 7,000 psi with 6.75% and 8.3% fines produced, respectively. Sample GFS-04 (fig. 14) produced the lowest percentage of

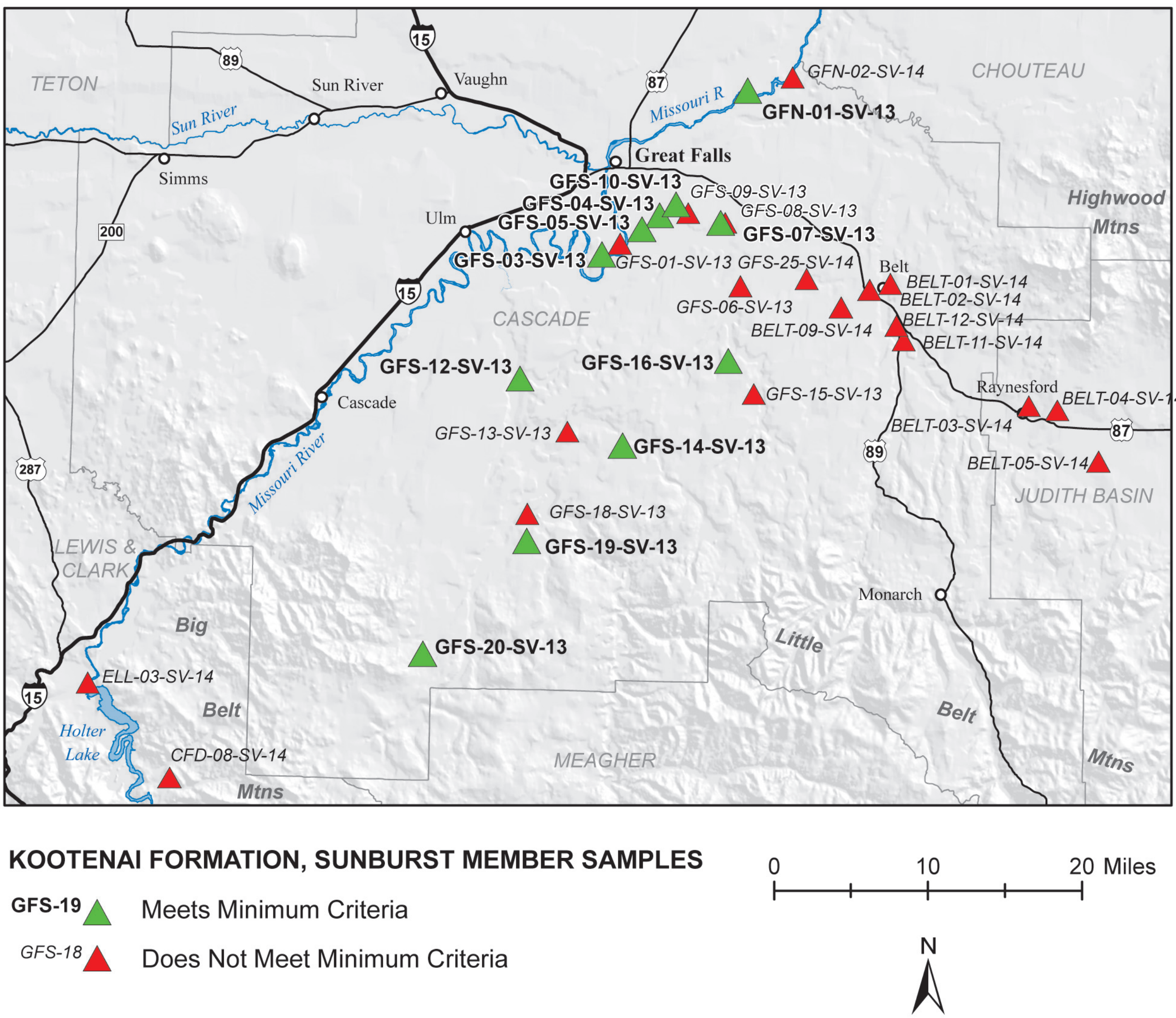


Figure 13. Sample locations—Kootenai Formation, Sunburst member, west-central Montana.

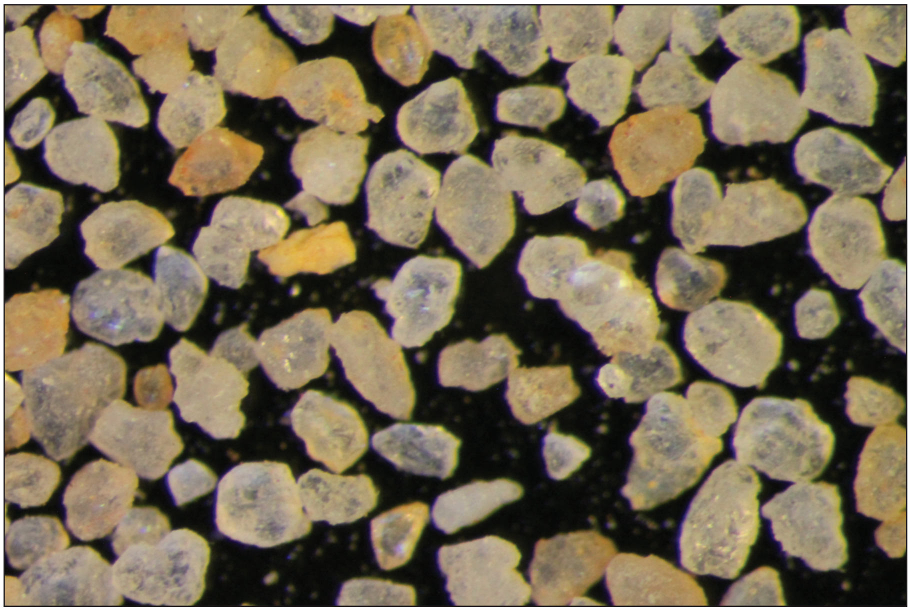


Figure 14. Microscopic view—Kootenai Formation, Sunburst member. Sample GFS-04 grains at 140 mesh size. This sample passed all preliminary tests and crush tests at 6,000 and 7,000 psi. Some quartz grains exhibit minor iron staining.

fines (8.8%) after crush testing at 7,000 psi and is an example of potential proppant material.

Table 6 summarizes the Sunburst member samples that met the minimum API criteria for proppant.

None of the samples collected near Belt, Montana (east–southeast of Great Falls), near where the Sunburst member pinches out, met the minimum proppant criteria.

The Sunburst member of the Kootenai Formation in areas near Great Falls, Montana contains sandstone that may have economic value as proppant. Samples from the Sunburst member of the Kootenai Formation that exceeded the API minimums are listed in table 6.

Kootenai Formation: Additional Samples

Eleven samples were collected from Kootenai Formation sandstone that were not associated with either the Greybull or Sunburst members. Eight of the samples were tested and their locations are shown in figure 15. Two of the eight samples, C81-01 and A33-01, passed testing. A33-01 passed crush tests at 6,000 and 7,000 psi (4.0% and 7.7% fines produced,

Table 6. Kootenai Formation, Sunburst member samples that met the minimum criteria for proppant.

							% Fines			
Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	5,000 psi	6,000 psi	7,000 psi	8,000 psi
GFN-01-SV-13	47.56971	-111.12045	CASCADE	70/140	0.653	0.657		9.3	12.9	
GFS-03-SV-13	47.41254	-111.31773	CASCADE	70/140	0.696	0.680		9.25	12.75	
GFS-04-SV-13	47.45054	-111.23826	CASCADE	70/140	0.644	0.641		6.5	8.75	10.5
GFS-05-SV-13	47.43757	-111.26246	CASCADE	70/140	0.638	0.651			9.9	12.5
GFS-07-SV-13	47.44667	-111.15008	CASCADE	40/70	0.678	0.571		6.75	8.25	11.43
GFS-10-SV-13	47.46126	-111.21637	CASCADE	70/140	0.640	0.548		8.75	11.9	
GFS-12-SV-13	47.29385	-111.42662	CASCADE	70/140	0.659	0.675	6.25	11.25		
GFS-14-SV-13	47.23266	-111.28306	CASCADE	70/140	0.652	0.683		7.5	10.25	11.75
GFS-16-SV-13	47.31526	-111.13943	CASCADE	70/140	0.655	0.681		7.55	9.92	12.91
GFS-19-SV-13	47.14088	-111.41181	CASCADE	70/140	0.667	0.674		8.0	10.25	16.66
GFS-20-SV-13	47.03229	-111.55112	CASCADE	70/140	0.662	0.651		5.78	10.76	

Note. Nearly all of the samples in this table met the sphericity and roundness criteria of 0.6. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

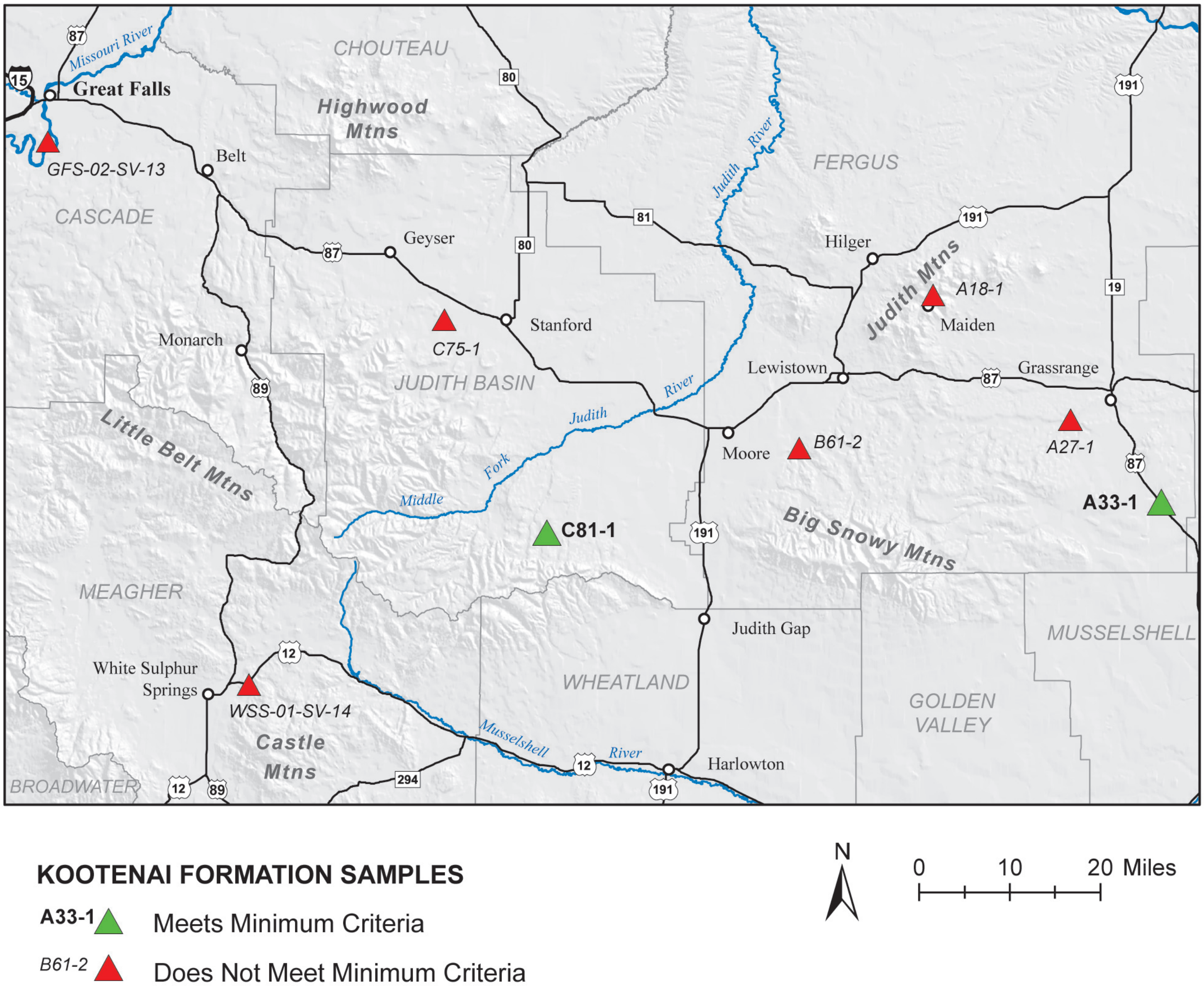


Figure 15. Sample locations—Kootenai Formation other than the Greybull or Sunburst members, central Montana.

respectively) and then failed crush testing at 8,000 psi with 12% fines produced. This sample was collected from the east side of the Big Snowy Mountains and further investigation of this area is warranted to determine if there is potential proppant from this part of the Kootenai Formation. Sample C81-01 passed crush testing at 5,000 psi (7.2% fines produced). The Kootenai Formation exposures near the Little Belt Mountains in the area where C81-01 was sampled are limited, resulting in the collection of only a few samples. Sample B61-02 contained a large fraction of non-quartz lithic components, and Samples B61-01, B61-03, and B61-04, collected from the same location as B61-02, were not tested for this reason.

Table 7 summarizes the results for the two samples from the Kootenai Formation that passed the minimum testing criteria for proppant.

Shedhorn Formation (Permian)

Five samples were collected from the Shedhorn Formation in the Gravelly Range in Madison County, Montana (fig. 16).

Samples ENN-11 and ENN-05 met the minimum criteria for proppant. ENN-11 produced 6.9% fines after 5,000 psi crush testing and 10.5% after crush testing at 6,000 psi. ENN-05 passed the crush test at 6,000 psi with 10.0% fines produced, and then failed crush testing at 7,000 psi with 13% fines produced (table 8). Testing was not completed on the remaining samples from this formation due to the presence of clusters at the dominant API size designation.

Table 8 summarizes the results for the Shedhorn Formation samples that met the minimum API criteria for proppant.

Table 7. Kootenai Formation samples other than Greybull or Sunburst members that met the minimum criteria for proppant.

Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	% Fines 6,000 psi	% Fines 7,000 psi	% Fines 8,000 psi
A33-1	46.86162	-108.68897	FERGUS	70/140	0.642	0.611		4.0	7.7	11.7
C81-1	46.81455	-110.12078	JUDITH BASIN	40/70	0.670	0.619	7.2			

Note. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. The red cell indicates that the percentage of fines produced at the 8,000 psi crush stress exceeded the 10% threshold in STD 19C. Both samples had adequate sphericity and roundness values.

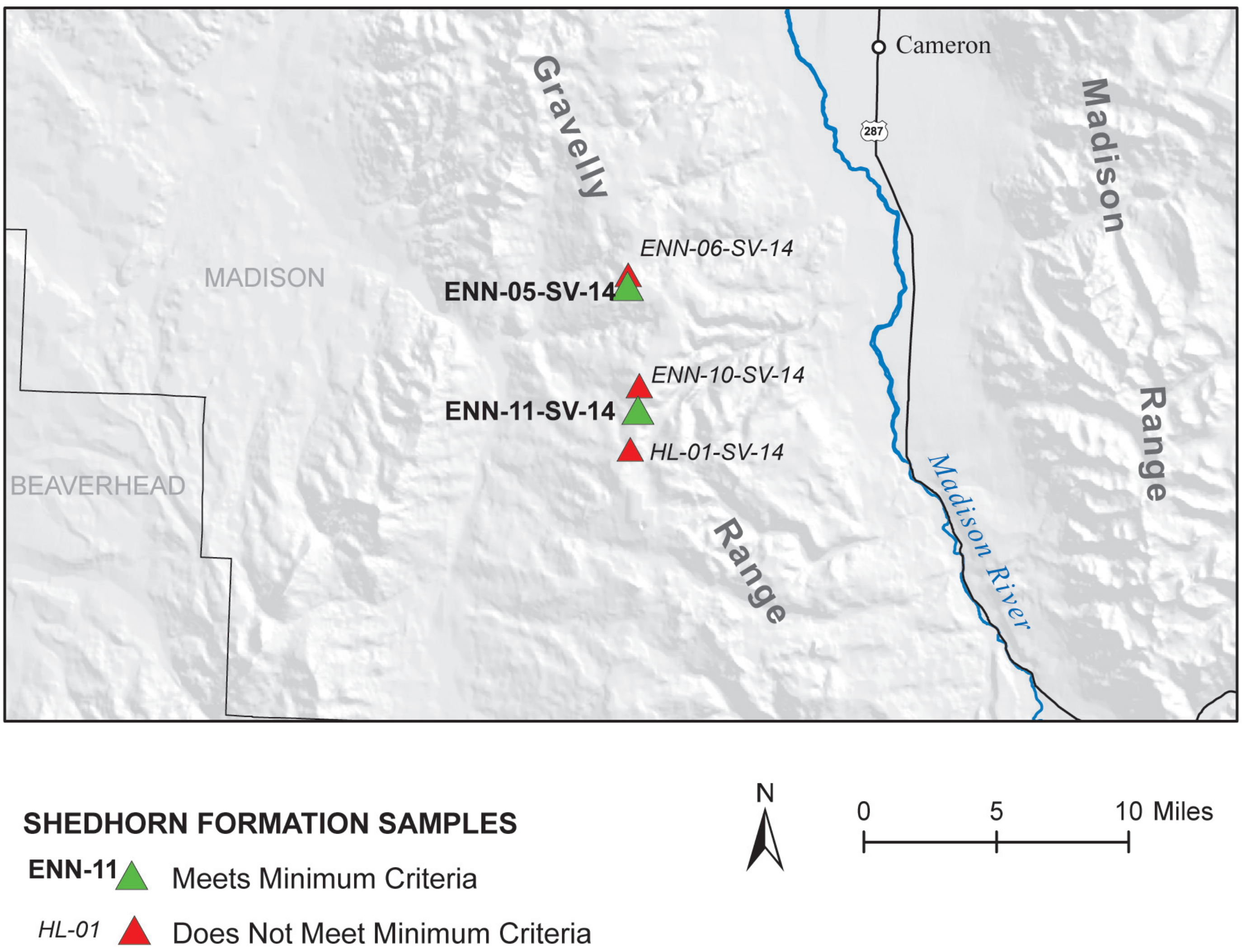


Figure 16. Sample locations—Shedhorn Formation, Madison County, southwest Montana.

Table 8. Shedhorn Formation samples that met the minimum criteria for proppant.

Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	6,000 psi	7,000 psi	8,000 psi
ENN-05-SV-14	45.068686	-111.867689	MADISON	70/140	0.648	0.627		10.0	13.2	
ENN-11-SV-14	45.001246	-111.856647	MADISON	70/140	0.657	0.642	6.9	10.5		

Note. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

Quadrant Formation (Pennsylvanian)

Fifty-two samples were collected from the Quadrant Formation in central and southwest Montana (figs. 17, 18). Table 3 summarizes the results for Quadrant samples from central Montana that met the minimum API criteria for proppant.

In the central part of Montana, five samples of the Quadrant from Lewis and Clark and Judith Basin Counties met the minimum criteria for proppant. Four samples (C82-2, C82-3, C84-1, and C85-1) that passed crush tests were located proximal to each other on the eastern flank of the Little Belt Mountains (fig. 17). Samples C82-1 through C85-3 were sampled from the same outcrop at different elevations. Sample C82-1

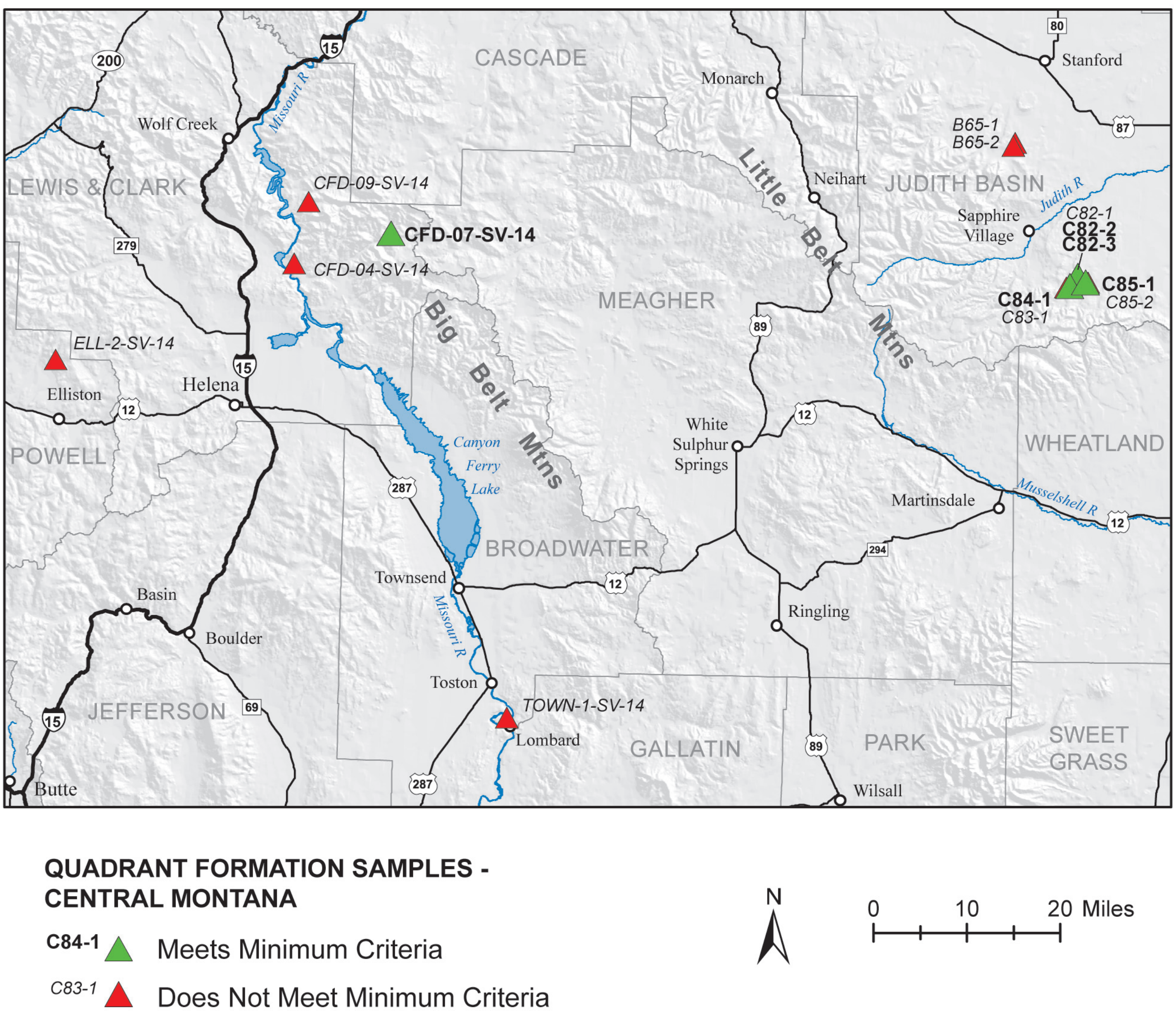


Figure 17. Sample locations—Quadrant Formation, west-central Montana.

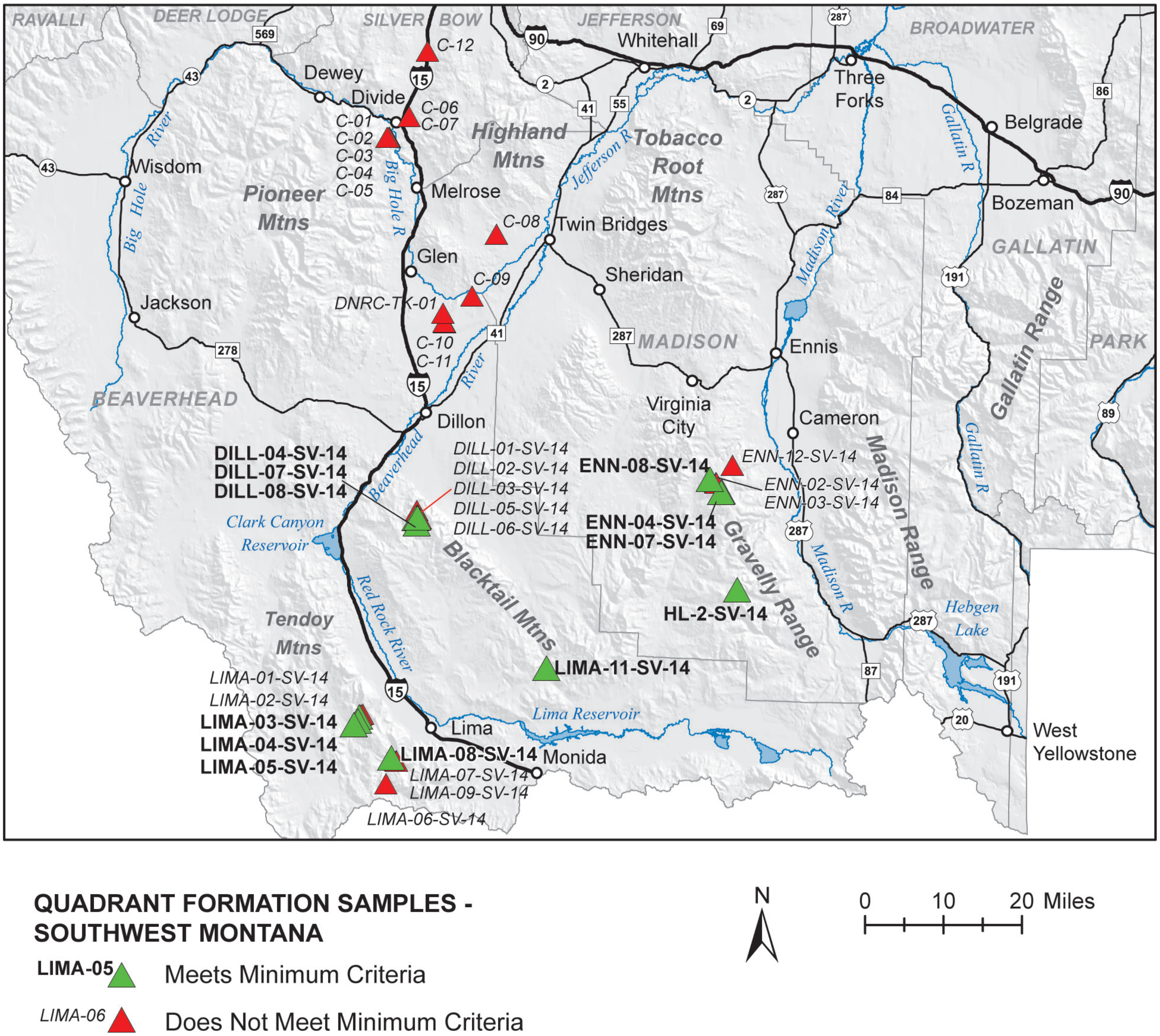


Figure 18. Sample locations—Quadrant Formation, southwest Montana.

failed crush tests but C82-2 and C82-3, sampled from higher in the section, passed (table 3). Based on the small number of samples, the material appears to be more suitable for proppant toward the top of the formation at this location. Also in Judith Basin County, samples C84-1 and C85-1 passed crush testing at 5,000 psi with 6.0 and 6.4 percent fines produced, respectively.

The sample CFD-07 in the Big Belt Mountains had a dominant API designation of 70/140, but fell just below the 10% threshold at 5,000 psi. At 6,000 psi the sample produced 14% fines, which does not meet minimum criteria.

We collected 38 samples from the Quadrant Formation in southwestern Montana (fig. 18). Table 9 summarizes results for Quadrant samples from this area that met the minimum API criteria for proppant.

All of the samples that showed promising results for proppant had API sieve sizes of 70/140. Therefore, the vast majority of potential proppant from the Quadrant Formation of southwestern Montana seems to be composed of fine to very fine sand grains according to the Wentworth standard sizing chart (appendix A). The most promising material from the Quadrant is located near Lima and Dillon. Two samples passed crush testing at crush strength of 7,000 psi: samples DILL-07 and LIMA-04. Grains collected in the 140 sieve for these samples are shown in figure 19.

Table 9. Quadrant Formation samples from southwestern Montana that met the minimum criteria for proppant.

Sample Name	Latitude	Latitude	County	Mesh Size	Spher-icity	Round-ness	% Fines 5,000 psi	% Fines 6,000 psi	% Fines 7,000 psi	% Fines 8,000 psi
C82-2	46.82038	-110.1416	JUDITH BASIN	70/140	0.639	0.664		6.4	12.3	
C82-3	46.82038	-110.1416	JUDITH BASIN	70/140	0.628	0.649		8.8		
C84-1	46.80445	-110.15912	JUDITH BASIN	70/140	0.626	0.656	6.0			
C85-1	46.81047	-110.12305	JUDITH BASIN	70/140	0.644	0.682	6.4			
CFD-07-SV-14	46.86801	-111.695397	LEWIS AND CLARK	70/140	0.669	0.628	10.0	14.0		
DILL-03-SV-14	45.023159	-112.653849	MADISON	70/140	0.659	0.682	5.7	10.4		
DILL-07-SV-14	45.013463	-112.651204	MADISON	70/140	0.639	0.654		5.5	6.6	12.2
DILL-08-SV-14	45.024181	-112.649685	MADISON	70/140	0.657	0.658		10.0	11.2	
ENN-04-SV-14	45.091799	-111.86168	MADISON	70/140	0.653	0.627		8.1	12.4	
ENN-07-SV-14	45.090977	-111.862455	MADISON	70/140	0.646	0.644		8.7		
ENN-08-SV-14	45.114751	-111.893332	MADISON	70/140	0.659	0.605		8.1	10.6	
HL-02-SV-14	44.911729	-111.813007	MADISON	70/140	0.641	0.613	7.9	10.2		
LIMA-03-SV-14	44.653248	-112.779823	BEAVERHEAD	70/140	0.656	0.614	8.3	13.0		
LIMA-04-SV-14	44.645591	-112.782381	BEAVERHEAD	70/140	0.657	0.655		7.9	8.8	12.5
LIMA-05-SV-14	44.637965	-112.791862	BEAVERHEAD	70/140	0.649	0.622		8.6	11.2	
LIMA-08-SV-14	44.579585	-112.692466	BEAVERHEAD	70/140	0.655	0.658	8.9	11.7		
LIMA-11-SV-14	44.756506	-112.30003	BEAVERHEAD	70/140	0.657	0.665	6.5	12.0		

Note. All of these samples had adequate sphericity and roundness values. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

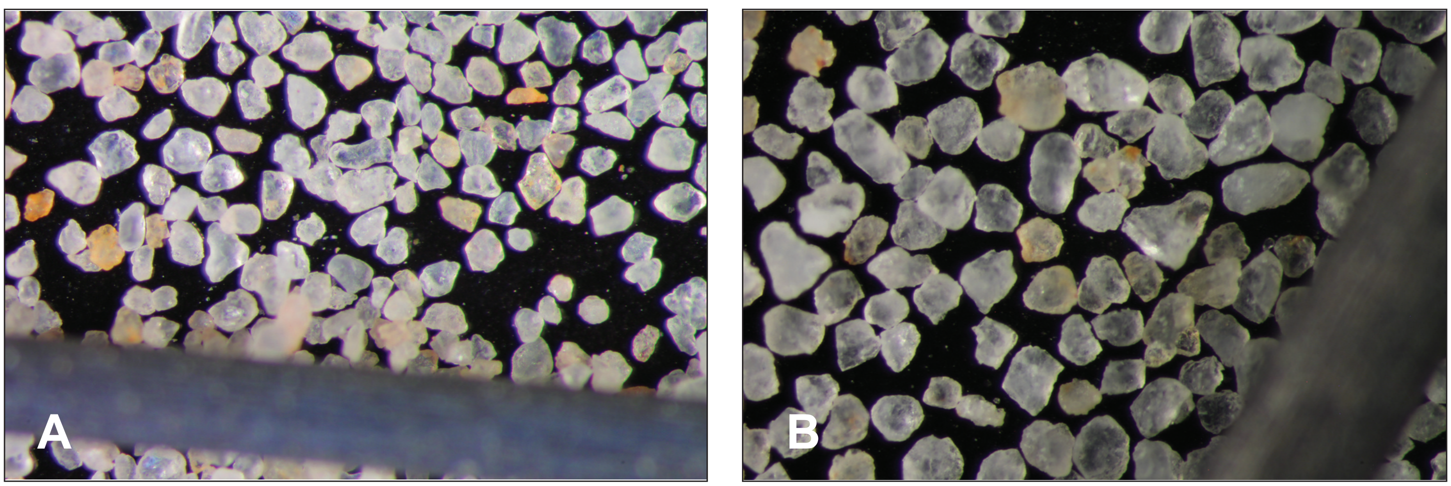


Figure 19. Microscopic view—Quadrant Formation, southwestern Montana. (A) Grains from sample DILL-07 at the 140 sieve size. (B) Grains from sample LIMA-04 at the 140 sieve size. Both samples have good sphericity and roundness as well as clarity and quartz content. Pencil lead (0.5 mm wide) for scale.

Tensleep Formation (Pennsylvanian)

Thirty-eight samples were collected from the Tensleep Formation in Bighorn and Carbon Counties, Montana (fig. 20). Four samples, shown with green symbols, met the minimum criteria for proppant. Samples A07-1 through A07-4 were sampled at the same location, up-section in 10-ft increments. Sample A07-1 was collected from a very fine-grained sandstone near the base of the outcrop in what appeared to be a dune deposit. The uppermost sample (A07-4) was collected from a massive sandstone that overlies the dune sandstones.

All of the samples from this formation showed good sphericity and roundness but also exhibited very fine grain size. Many samples showed clusters even at a mesh size of 140. Samples A07-1 and A07-3 met the minimum criteria for proppant and passed crush tests at 6,000 psi (7.8% fines produced) and 5,000 psi (9.61% fines produced), respectively. These two samples were collected from dune sandstone, whereas

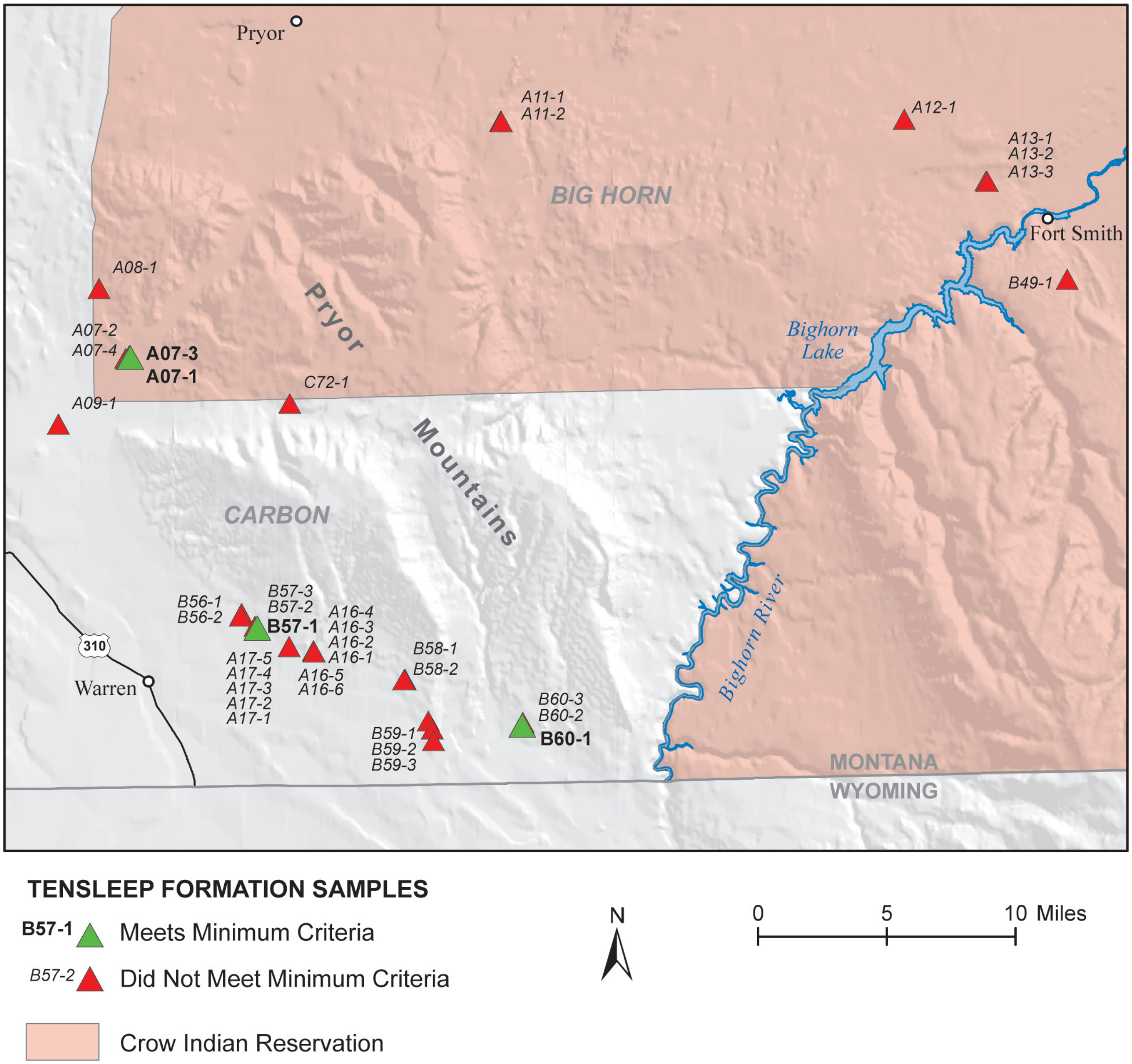


Figure 20. Sample locations—Tensleep Formation, south-central Montana.

"failed" samples A07-2 and A07-4 were collected from intervening beds of marine sandstones.

Figure 21 provides several views of an outcrop of the Tensleep formation. Truncated human parts are shown for scale.

B57-1 was the only sample from the Tensleep Formation that passed crush testing at 6,000 and 7,000 psi (6.0% and 7.7% fines produced, respectively). Sample B60-1 passed 5,000 psi crush testing with 8.8% fines produced. Samples B57-1 and B60-1 were collected along the southwest side of the Pryor Mountains and were composed of very fine-grained, white, friable sandstone with potential for use as proppant if small particle size is acceptable.

Figure 22A shows the sampled outcrop and figure 22B shows quartz grains from sample B57-1 from the 140 sieve size under a microscope. These quartz grains are rounded, semi-spherical, and show high clarity.

The upper part of the Tensleep Formation is composed of alternating cycles of eolian dune sandstone and calcareous shallow marine sandstone (Lopez and VanDelinder, 2007). Although none of the marine sandstones passed the minimum criteria, eolian dune sands may have potential as viable proppant material. The interbedding of dune sandstone with calcareous marine sandstones could make quarrying a challenge. Therefore, a more thorough investigation of dune sandstone within the upper Tensleep Formation

Figure 21. Outcrop view—Tensleep Formation. (A) Lower dune sandstone, very fine grained where sample A07-1 was collected. (B) Outcrop of reworked marine sandstone where sample A07-2 was collected. (C) Contact between cross-bedded dune sandstone (A07-3 sample) and marine sandstone (A07-4 sample).

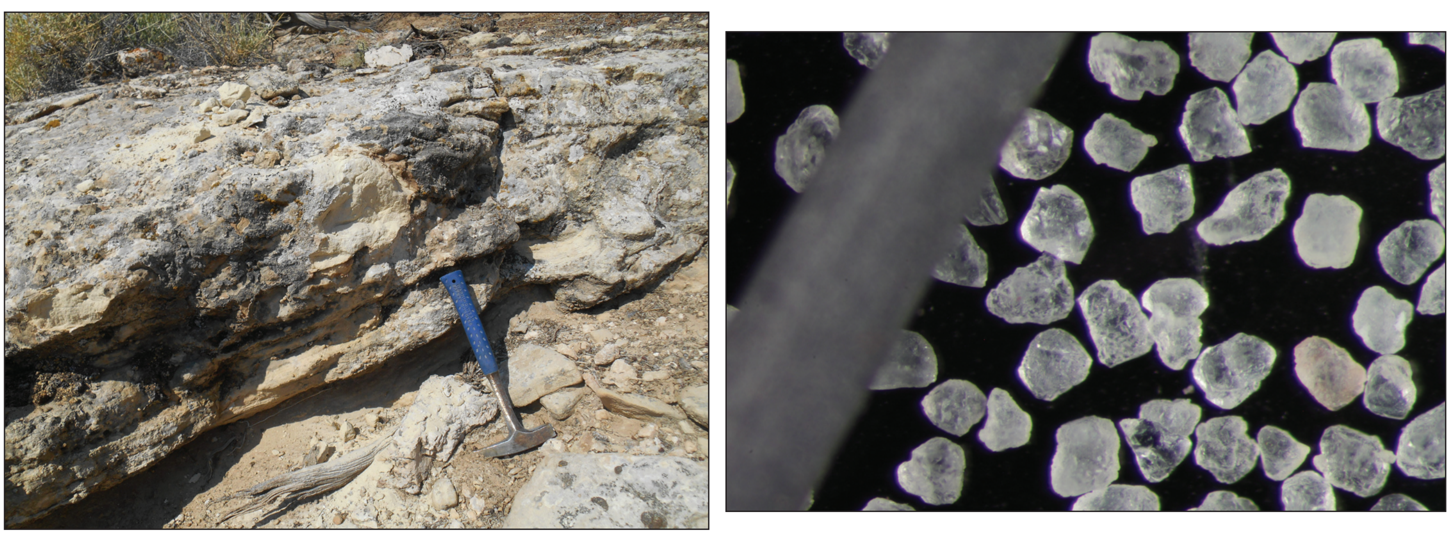


Figure 22. Outcrop and microscopic views—Tensleep Formation, sample B57-1. (A) Outcrop of friable, white, dune sandstone where sample was collected. (B) Microscopic view of sample at the 140 sieve size. Pencil lead (0.5 mm wide) for scale.

Table 10. Tensleep Formation samples that met the minimum criteria for proppant.

Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	6,000 psi	7,000 psi	8,000 psi
A07-1	45.24218575	-108.6739454	CARBON	70/140	0.633	0.641		7.8	12.3	
A07-3	45.24236238	-108.6739088	CARBON	70/140	0.635	0.602	9.61	12.17	13.8	
B57-1	45.09027	-108.57377	CARBON	70/140	0.635	0.654	6.0	7.7	12.8	
B60-1	45.03252	-108.36217	CARBON	70/140	0.643	0.648	8.8	14.6		

Note. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

may be important. Table 10 summarizes results for Tensleep samples that met the minimum API criteria for proppant.

Tyler Formation (Pennsylvanian and Mississippian)

Thirty-four samples were collected from the Tyler Formation in Fergus and Judith Basin Counties, Montana (fig. 23).

Twenty-one samples met the minimum criteria for proppant, which is the highest percent of passing samples of any formation investigated in this study.

These samples were collected in the northeastern part of the Little Belt Mountains and the northern part of the Big Snowy Mountains. Table 11 summarizes the results for Tyler samples that met the minimum API criteria for proppant.

Sample B67-1 was the only sample in this study that successfully passed crush testing at 8,000 psi, producing 8.5% fines. This sample is located along the north side of South Fork Flatwillow Creek in the Big Snowy Mountains. Sample B67-2 was collected nearby, to the east, in an area with a mixture of lithologies including shale, conglomerate, limestone and sandstone. This sample failed all crush tests. An example of the 140 mesh quartz grains from sample B67-1 is

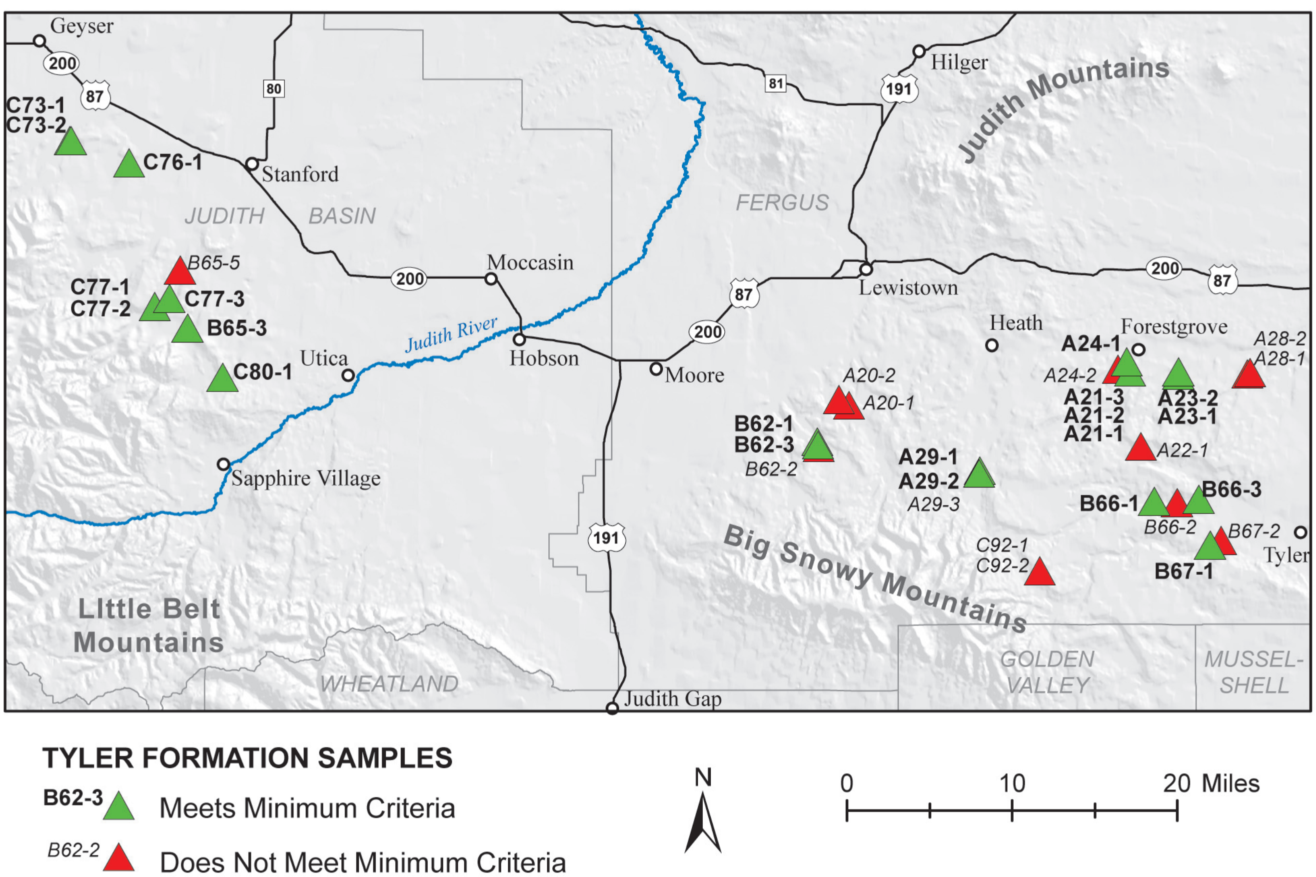


Figure 23. Sample locations—Tyler Formation, central Montana.

Table 11. Tyler Formation samples that met the minimum criteria for proppant.

Sample Name	Latitude	Longitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	6,000 psi	7,000 psi	8,000 psi	9,000 psi
A21-1	46.97243	-109.09127	FERGUS	70/140	0.622	0.592		7.03	9.11	12.28	
A21-2	46.97243	-109.09127	FERGUS	70/140	0.623	0.647		8.2	12		
A21-3	46.97243	-109.09127	FERGUS	70/140	0.632	0.644		7.6	9.64	13.9	
A22-1	46.907234	-109.077612	FERGUS	70/140	0.593	0.553		8	11.4		
A23-1	46.96918	-109.02905	FERGUS	70/140	0.638	0.574	9.86	15.91	20.1		
A23-2	46.9721	-109.02908	FERGUS	70/140	0.640	0.689		8.45	13.25		
A24-1	46.98163	-109.09573	FERGUS	70/140	0.631	0.677		8.9	12.12		
A29-1	46.88687	-109.28395	FERGUS	70/140	0.654	0.658			8.5	11.75	
A29-2	46.88415	-109.28497	FERGUS	70/140	0.641	0.585		6.63	14.55		
B62-1	46.91205	-109.4917	FERGUS	40/70	0.647	0.696	8.7				
B62-3	46.90927	-109.49102	FERGUS	70/140	0.625	0.647	5.6				
B65-3	47.00885	-110.2999	JUDITH BASIN	70/140	0.626	0.644		8.2	10.6		
B66-1	46.85882	-109.06102	FERGUS	40/70	0.616	0.626	9.3	10	21.3		
B66-3	46.86028	-109.00408	FERGUS	70/140	0.627	0.683	8.1	10.6			
B67-1	46.82002	-108.99008	FERGUS	70/140	0.644	0.673		4.8	7.1	8.5	10.1
C73-1	47.17187	-110.45433	JUDITH BASIN	70/140	0.640	0.667		5.7	4.4		
C73-2	47.17197	-110.45218	JUDITH BASIN	70/140	0.634	0.680	6.9				
C76-1	47.15337	-110.37785	JUDITH BASIN	70/140	0.639	0.679		9.2	10.5		
C77-1	47.02721	-110.34262	JUDITH BASIN	70/140	0.640	0.657	8.6				
C77-2	47.02729	-110.34235	JUDITH BASIN	70/140	0.636	0.667	6.6				
C77-3	47.03485	-110.32383	JUDITH BASIN	70/140	0.630	0.665	4.4				
C80-1	46.96618	-110.2544	JUDITH BASIN	70/140	0.629	0.679	3.9				

Note. All samples in this table had adequate or nearly adequate sphericity and roundness values. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

shown in figure 24. The quartz grains are rounded (0.673) and spherical (0.644) with good clarity and no lithic fragments.

Tyler Formation outcrops on the northeastern side of the Little Belt Mountains appear to contain material with potential for use as proppant. Only one sample there (B65-5) failed to meet proppant criteria; it was the only sample near the Little Belt Mountains with an API size designation larger than 70/140. The sandstones from the Tyler in this area with API size of 70/140 consistently met minimum criteria for proppant material. In addition, approximately half the samples from the northern Big Snowy Mountains met minimum criteria for proppant. The Tyler Formation has the most consistent positive results for proppant material of those sampled in Montana and is a potential source for quality proppant, with some potential to withstand pressures of up to 8,000 psi.

Kibbey Formation (Mississippian)

Fifteen samples were collected from the Kibbey Formation, most of which were located around the Little Belt Mountains (fig. 25). Sample B64-2 had an API size at 70/140 and was the only Kibbey sample that passed all lab tests. Its sphericity and roundness values were 0.665 and 0.680, respectively; it passed a crush test at 6,000 psi with 9.5% fines produced, then failed at 7,000 psi with 12.7% fines produced. The API grain sizes of the samples from this formation are highly variable, and 11 of the 15 samples failed to meet minimum criteria for proppant material because of the presence of clusters at the designated API sieve sizes. An investigation of the area to the east and

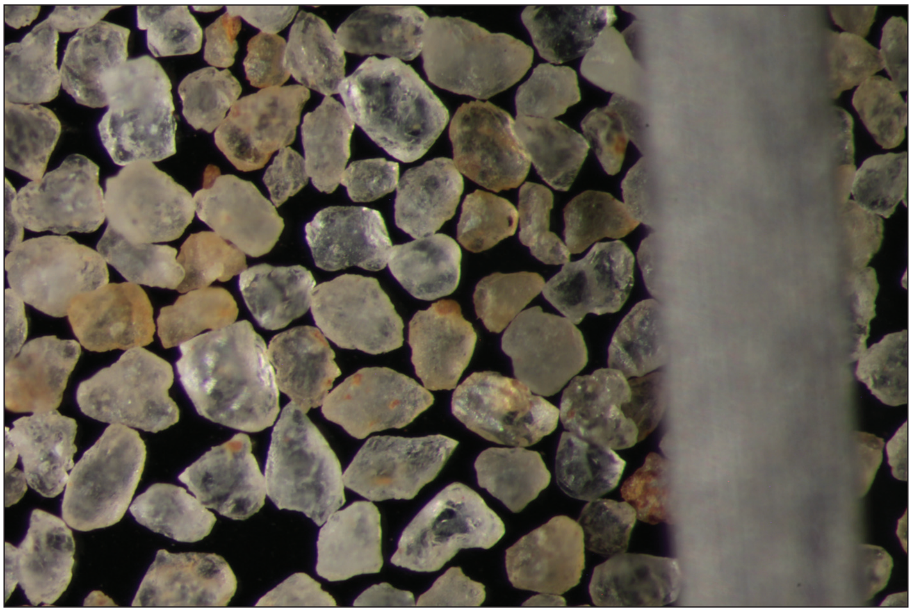


Figure 24. Microscopic view—Tyler Formation, B67-1 at the 140 mesh size. Pencil lead (0.5 mm) for scale.

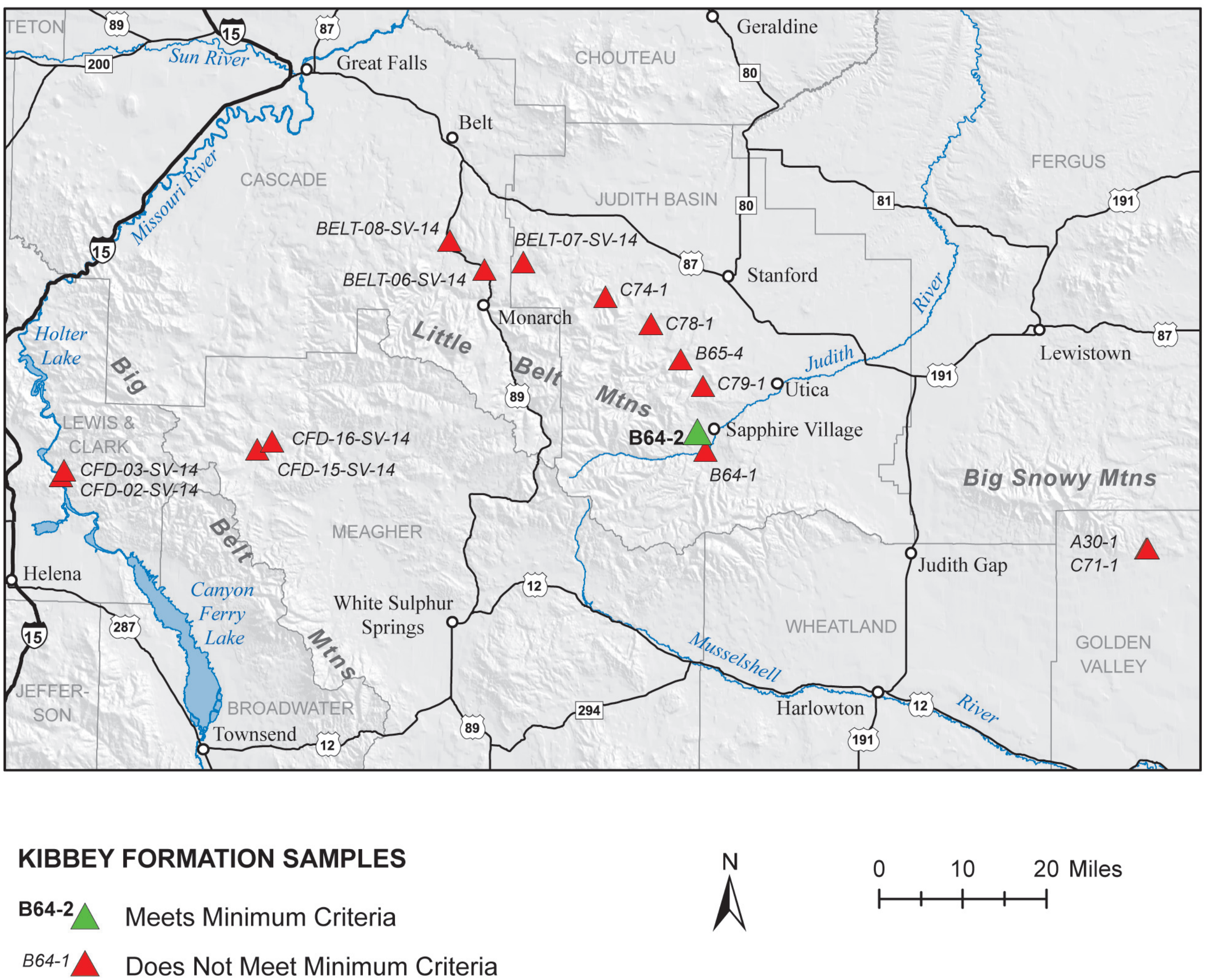


Figure 25. Sample locations—Kibbey Formation, central Montana.

south of sample B64-2 could provide a more complete evaluation of this formation.

Table 12 summarizes the results for the only sample of the Kibbey Formation that met the minimum API criteria for proppant.

Flathead Formation (Cambrian)

Twenty-five samples were collected and processed from the Lower Cambrian Flathead Formation, the oldest sandstone with proppant potential of those sampled in Montana (fig. 26). Four samples met the minimum criteria for proppant. Most of the Flathead samples were collected from the Big Belt and Little Belt Mountains where cementation is the least pronounced; however, samples were also taken from Missoula, Jefferson, Gallatin, and Powell Counties.

Table 12. Kibbey Formation sample that met the minimum criteria for proppant.

Sample Name	Latitude	Latitude	County	Mesh Size	Sphericity	Roundness	% Fines 5,000 psi	% Fines 6,000 psi	% Fines 7,000 psi	% Fines 8,000 psi
B64-2	46.88512	-110.294	JUDITH BASIN	70/140	0.665	0.680		9.5	12.7	

Note. Sample had good sphericity and roundness. Green cell indicates that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cell indicates that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

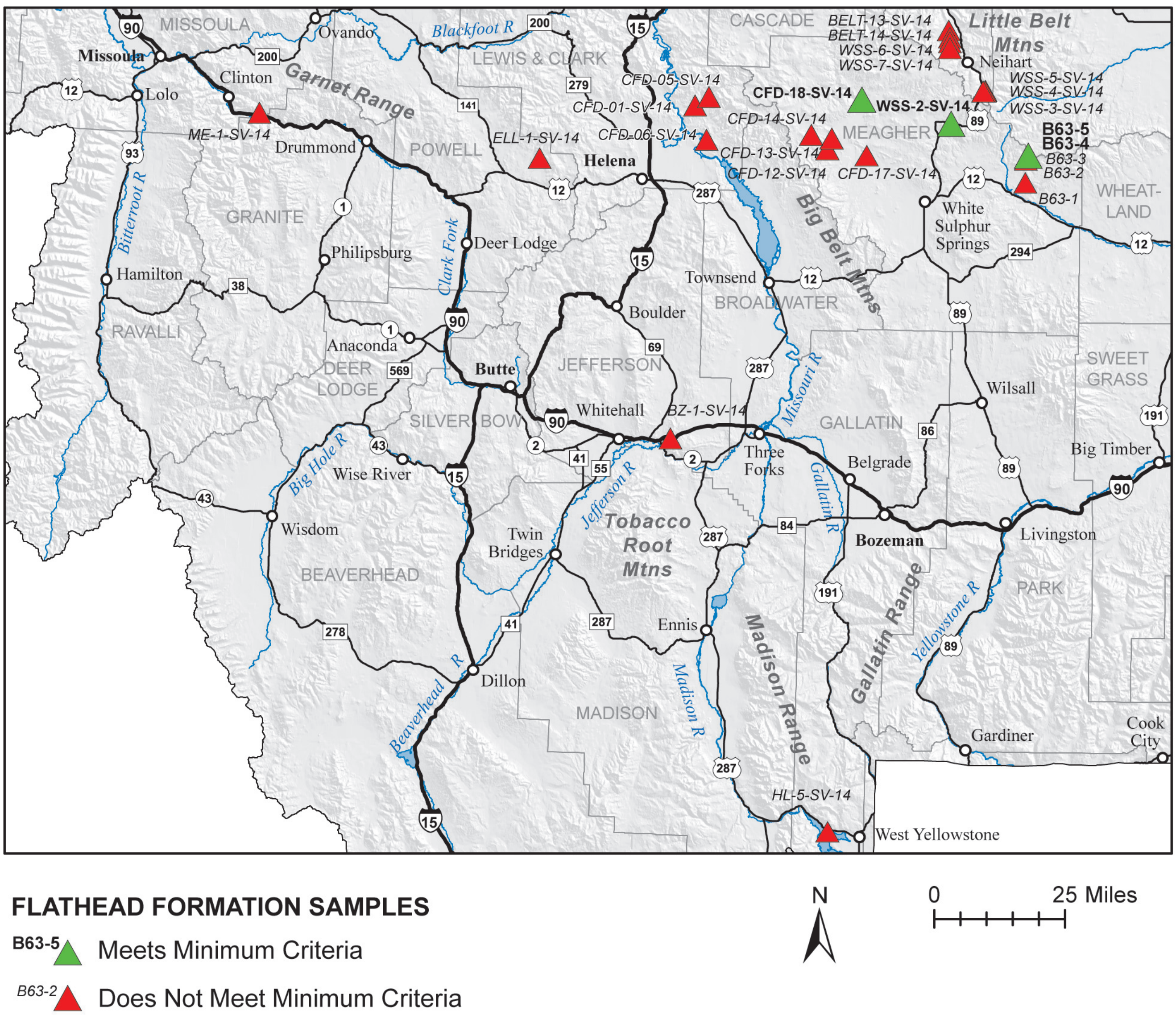


Figure 26. Sample locations—Flathead Formation, central and southwestern Montana.

Table 13 summarizes the results for the four Flathead samples that met the minimum API criteria for proppant. These samples were located along the southwestern flank of the Little Belt Mountains (fig. 26). Samples that passed crush tests included B63-4 and B63-5. These samples show increased grain size and increased iron staining (perhaps from the presence of hematite) down-section. Sample CFD-18 was located farthest west along the southwest side of the Little Belt Mountains and contained abundant limonite specks. This was the only sample that passed a 6,000 psi crush test. The microscopic view of CFD-18 is shown in figure 27.

The Flathead Formation on the southwest side of the Little Belt Mountains might prove to be a source of quality proppant sand that can consistently pass 5,000 psi crush tests.

Formations not Yielding Positive Results

This project was designed to provide guidance on sandstones within the State of Montana that have some promise as sources of proppant material. Perhaps as important as those samples that showed potential, however, are results that indicate formations that are less likely or unlikely to provide viable proppant. Three of the units were initially identified as target sandstones (Virgelle Formation, Fall River Formation, and Flood Member of the Blackleaf Formation). The others were not target sandstones.

This section details the laboratory and geology results for formations that did not meet the minimum API criteria for proppant. Figure 28 shows the general location of the samples for each formation.

Table 13. Flathead Formation samples that met the minimum criteria for proppant.

							% Fines			
Sample Name	Latitude	Latitude	County	Mesh Size	Sphericity	Roundness	5,000 psi	6,000 psi	7,000 psi	8,000 psi
B63-4	46.68257	-110.49058	MEAGHER	30/50	0.658	0.597	9.4	11.3		
B63-5	46.68257	-110.49058	MEAGHER	40/70	0.647	0.664	7.3	11.7		
CFD-18-SV-14	46.829335	-111.16383	MEAGHER	70/140	0.632	0.587		6.4	10.3	
WSS-02-SV-14	46.767276	-110.804047	MEAGHER	30/50	0.633	0.604	8.9	14.0	20.3	

Note. The sand-grain roundness of two of the samples is marginal. Green cells indicate that the percentage of fines produced at a particular crush stress was acceptable for proppant. Red cells indicate that the percentage of fines produced at a particular crush stress exceeded the 10% threshold in STD 19C.

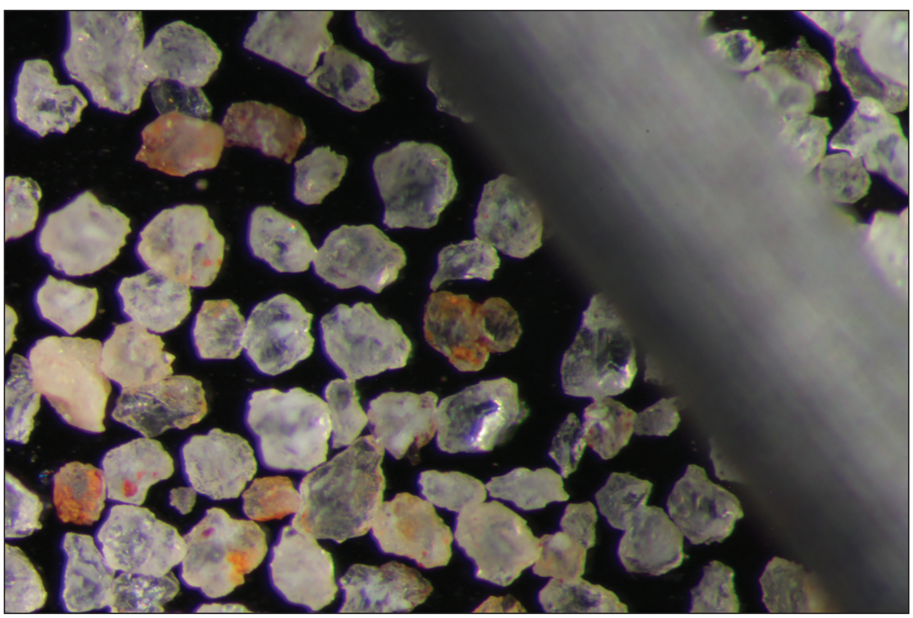


Figure 27. Microscopic view—Flathead Formation, sample CFD-18 at 140 mesh size. Primarily composed of quartz with no lithic clasts in this view. Limonite coats some of the grains. Pencil lead (0.5 mm wide) for scale.

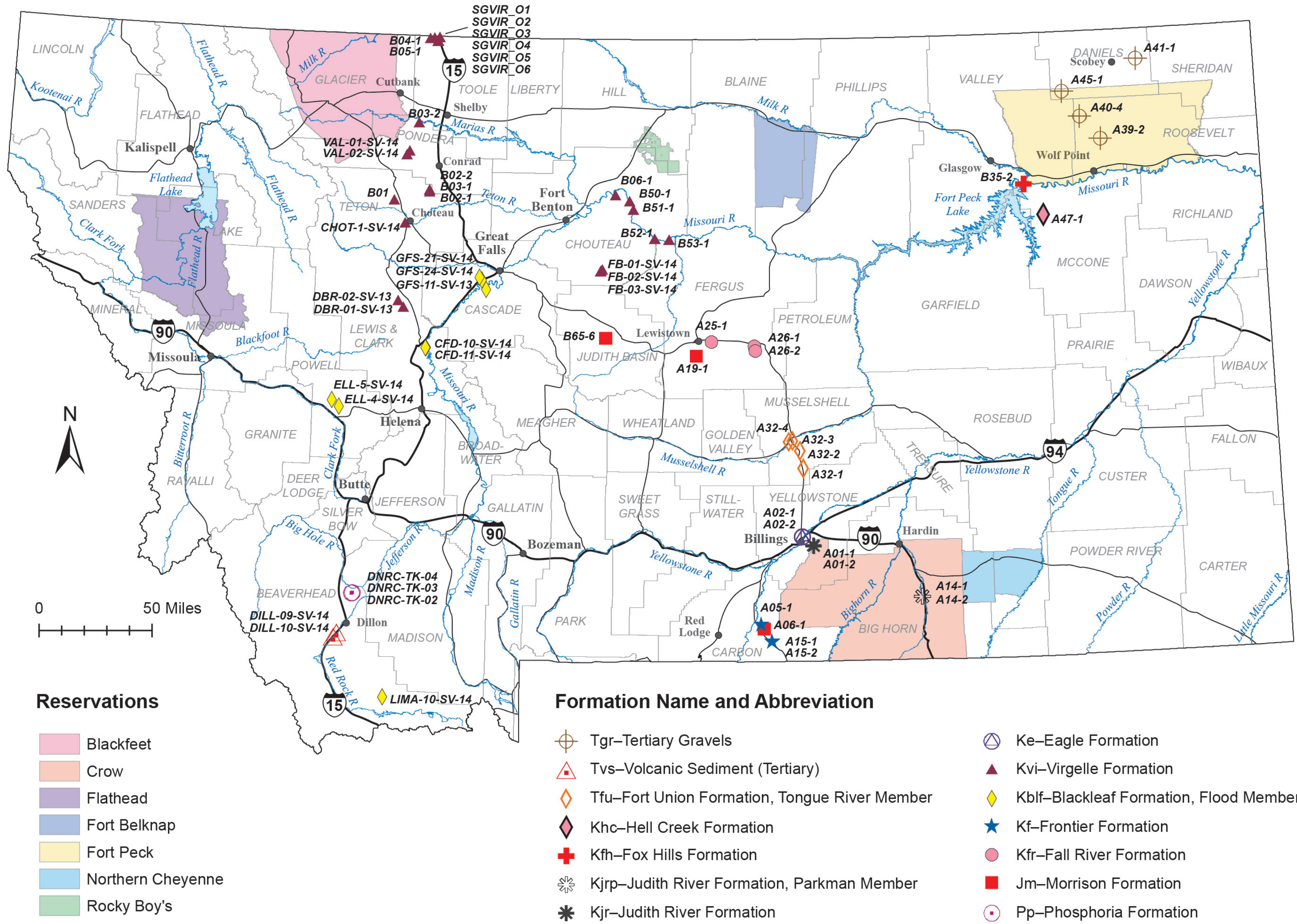


Figure 28. Sample locations—formations that did not yield promising results.

Fort Union Formation: Tongue River Member (Tertiary)

Four samples were collected in Musselshell County (fig. 28) from the Tongue River Member of the Fort Union Formation.

Samples A32-1 and A32-2 contained significant amounts of lithic fragments so further testing was ruled out. Samples A32-3 and A32-4 passed the requirements for sphericity (0.611 and 0.643, respectively) and roundness (0.596 and 0.602, respectively) but failed crush tests at both 5,000 (20.3% and 13.5% fines produced, respectively) and 6,000 psi (21.9% and 15.3% fines produced, respectively). With the high percentage of lithic material and low crush results obtained for these samples, it is unlikely that material from the Tongue River Member of the Fort Union Formation in this area will be a viable source of proppant.

Hell Creek Formation (Upper Cretaceous)

Sample A47-1 (fig. 28) from the Hell Creek Formation in McCone County had an API size of 70/140; however, when the sample was examined with the optical microscope (fig. 29), it was evident that there were many lithic clasts present. In addition, the grains were angular and did not exhibit adequate sphericity, so further testing was abandoned.

Fox Hills Formation (Upper Cretaceous)

The Fox Hills Formation was sampled in one location in the northwestern corner of McCone County in northeastern Montana (fig. 28). Although Sample B35-2 showed marginal sphericity (0.603) and roundness (0.587), it failed under pressures of 6,000 and 5,000 psi with 43.9% and 37.9% fines produced, respectively, making it unsuitable for proppant material. The micrograph of the 140 mesh material (fig. 30) showed a large amount of lithic clasts and several clusters, explaining the poor crush results. Iron staining and other contaminants are also present. If sample B35-2 is typical of the Fox Hills Formation, it is unlikely to be a viable source of proppant.

Eagle Formation (Upper Cretaceous)

Two samples from the Eagle Formation, A02-1 and A02-2, were collected from an outcrop in Billings, Montana (fig. 28). The outcrop and a microscopic view of sample A02-1 are shown in figure 31. The samples have a vertical separation of approximately 13 ft and were divided by the presence of a lightly vegetated area. Both of these samples failed because of grain size in the silt range. Based on the microscopic view, it is evident that these Eagle Formation samples would not pass sphericity and roundness in addition to being too fine grained for potential proppant material.

Frontier Formation (Upper Cretaceous)

Three samples were collected from the Frontier Formation in southern Montana in Carbon County (fig. 28).

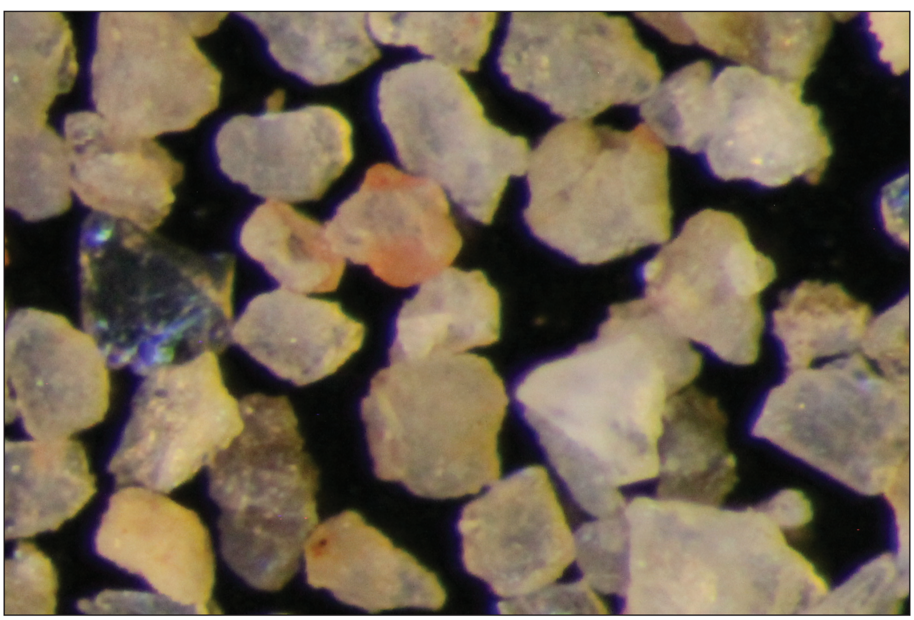


Figure 29. Microscopic view—Hell Creek Formation, sample A47-1, 140 mesh. Abundant lithic clasts and poor sphericity/roundness indicate that this sample does not pass the minimum requirements for proppant.

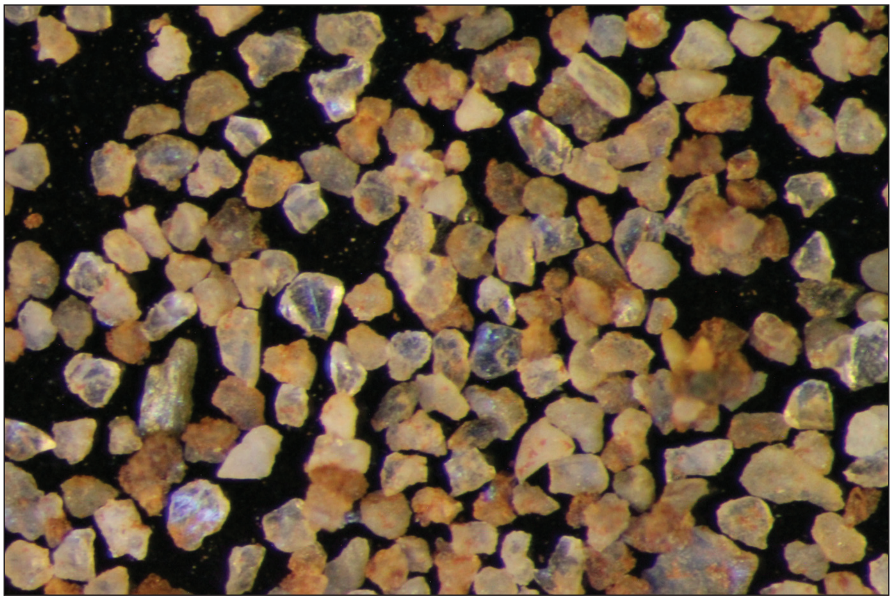


Figure 30. Microscopic view—Fox Hills Formation. Sample B35-2, 140 mesh retrieval, northeastern Montana, showing the large percentage of lithic material in this sample.

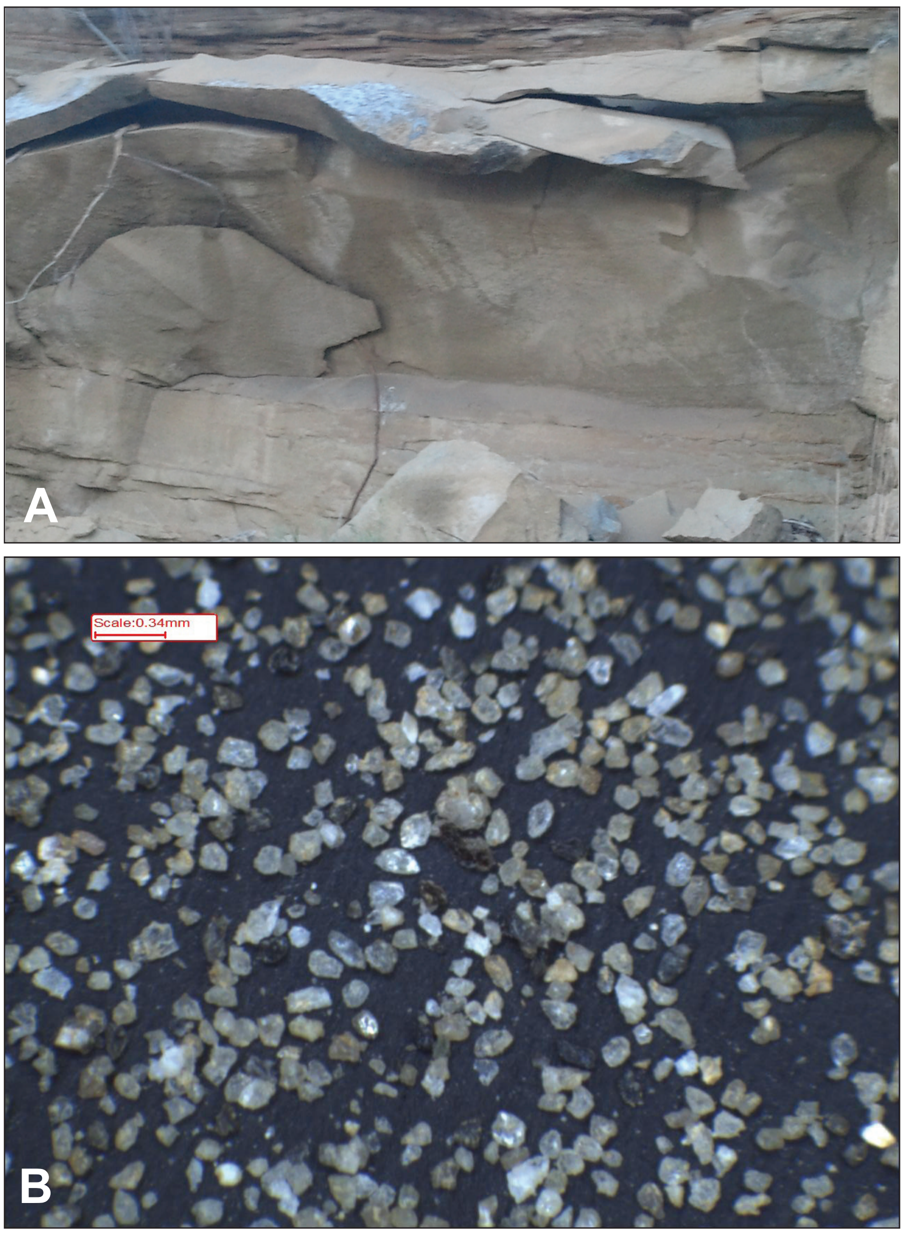


Figure 31. Eagle Formation, sample A01-1, near Billings, Montana. (A) Outcrop view. (B) Microscopic view. The grains are silt size rather than sand.

The northernmost sample (A5-01) was determined to be mudstone with lithic clasts and minimal quartz present. Figure 32 shows a field microscopic view of the sample from the Frontier Formation.

Samples A15-01 and A15-02 were collected from the same outcrop area. Sample A15-02 was approximately 7 ft lower in elevation and on the other side of a gully from A15-01. Both samples returned API sizes of 70/140; however, they were not tested further because of the presence of grain clusters (A15-01) and too many lithic clasts (A15-02), as shown in figure 33.

Fall River Formation (Lower Cretaceous)

The Cretaceous Fall River Formation, equivalent to the Flood Member of the Blackleaf Formation to the west, was sampled east of Lewistown in Fergus County (fig. 28). Three samples were collected and tested.

The IPSA (CAMSIZER) indicated that the appropriate API sieve size was 70/140; however, microscope pictures showed that individual quartz grains are actually smaller. Abundant quartz-grain clusters are visible in the 140 sieve from sample A26-1 (fig. 34). When disaggregated these clusters produced grains that are too small and preclude the Fall River Formation from serving as proppant material at these sample locations.

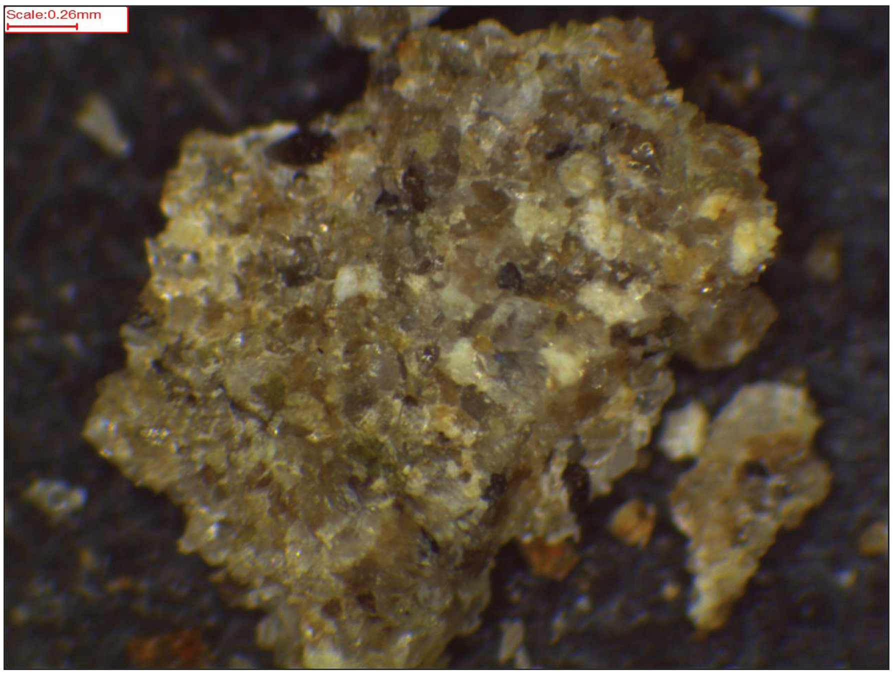


Figure 32. Frontier Formation, sample A05-1. A field micrograph shows an abundance of darker minerals, indicating that this sample may contain too much lithic material for proppant.

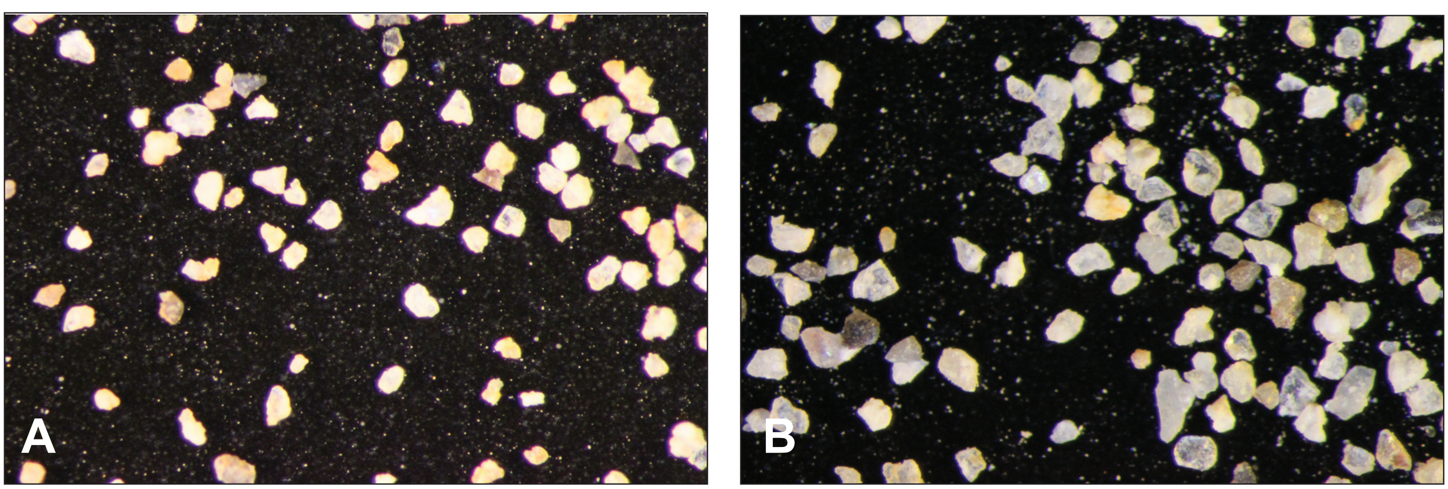


Figure 33. Microscopic view—Frontier Formation. (A) Sample A15-01 showing the 140 mesh sand grains and clusters. (B) Sample A15-02 at 140 mesh size showing angular sand grains with abundant lithic fragments.

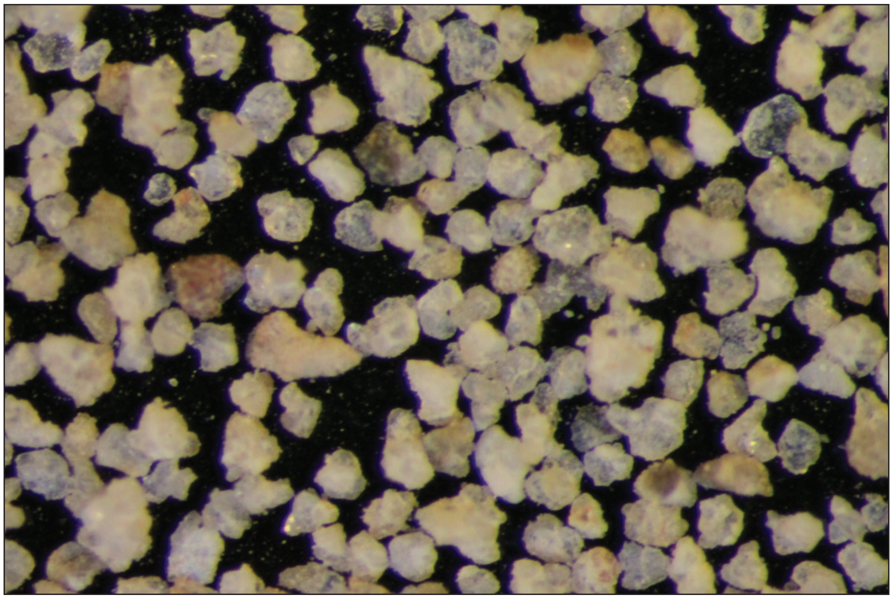


Figure 34. Microscopic view—Fall River Formation, sample A26, 140 mesh size, showing a predominance of clusters.

Judith River Formation

Samples A01-1 and A01-2 (fig. 35) from the Judith River Formation were collected from Yellowstone County in southern Montana (fig. 28).

Samples A01-1 and A01-2 failed due to the small grain size (fig. 35).

Judith River Formation: Parkman Member

Two samples (A14-1, A14-2) were collected from the Parkman Member of the Judith River Formation in Big Horn County, in south-central Montana (fig. 28). The outcrop was composed of a friable sandstone with abundant cross-bedding. Sample A14-1 was taken from the bottom 10 ft (tan sandstone) of the outcrop and sample A14-2 was taken from the top 30 ft of the outcrop (white, very fine-grained sandstone).

The view under the optical microscope shows the sand does not contain a high enough percentage of quartz to be considered for proppant. The sphericity for sample A14-1 was 0.581, and the roundness was 0.471, which do not meet the minimum requirements for further testing. Sample A14-2 was not tested for sphericity and roundness because of the abundance of lithic fragments visible in the microscopic view. Figure 36 shows the outcrop where samples A14-1 and A14-2 were collected. Figure 37 shows sample A14-1 and A14-2 in microscopic view where abundant lithic fragments and angular sand grains are visible.

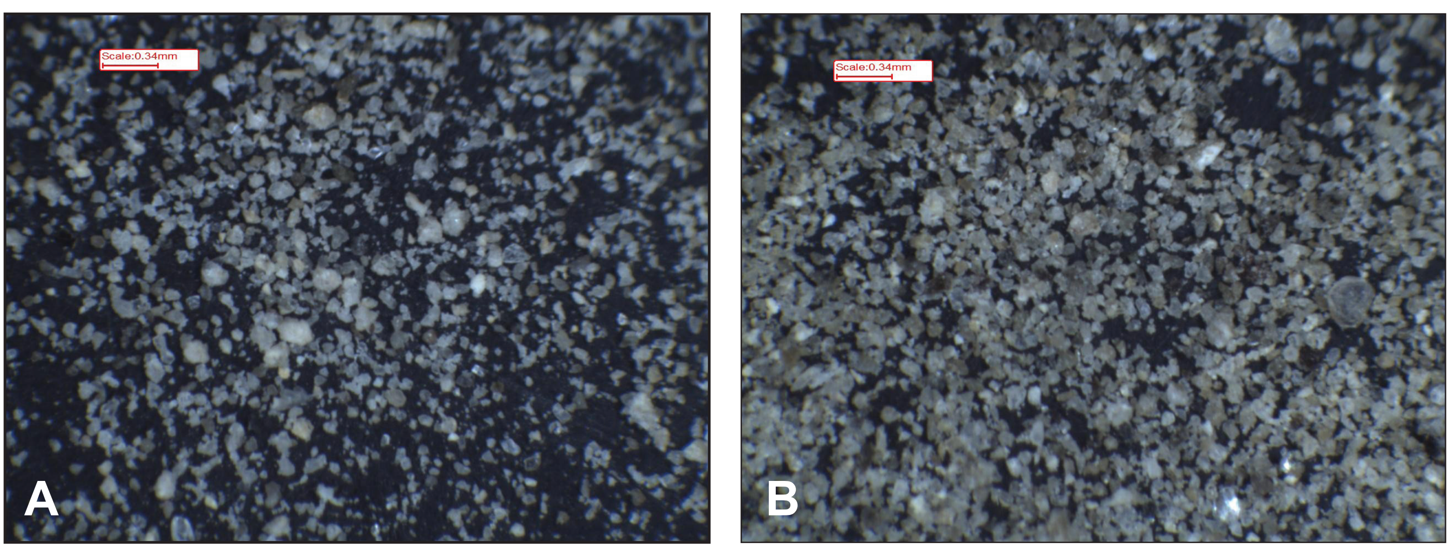


Figure 35. Microscopic view—Judith River Formation. (A) Sample A01-1 (B) Sample A01-2. Both samples contain grains that are too small to warrant further testing.

Figure 36. Outcrop view—Judith River Formation, Parkman Member, where samples A14-1 and A14-2 were collected. Rock hammer shown for scale.

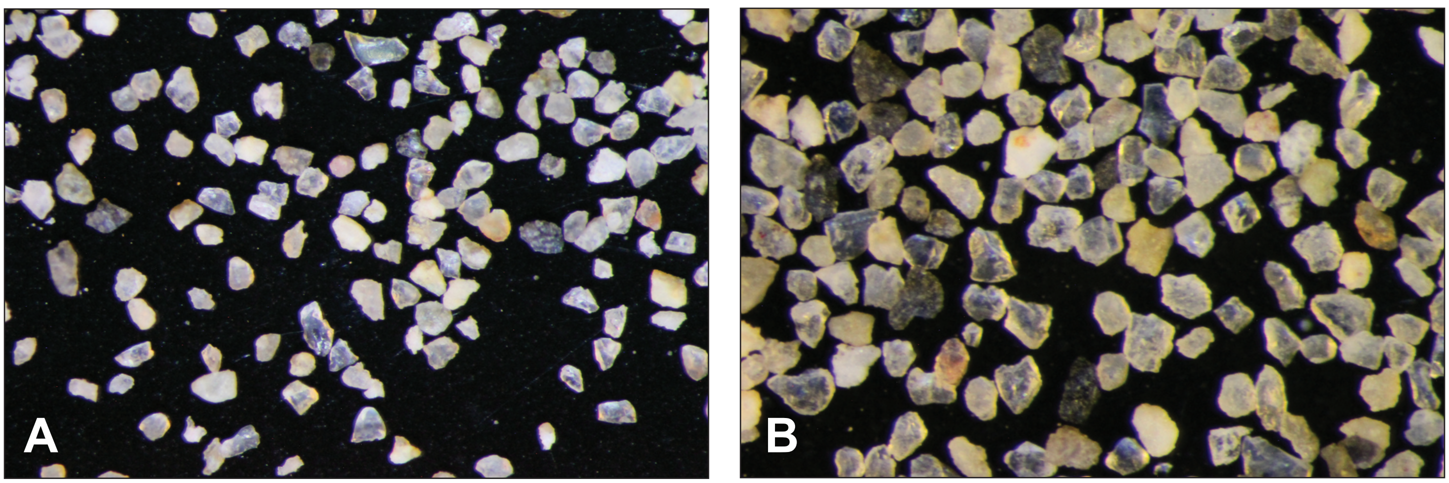


Figure 37. Microscopic view—Judith River Formation, Parkman Member A. Sample A14-1 at the 140 mesh size showing many dark lithic fragments and angular sand grains. (B) Sample A14-2 at the 140 mesh size showing grains slightly larger and more rounded than A14-1 but with similar amounts of lithic clasts.

Morrison Formation (Jurassic)

Three samples were collected from the Morrison Formation in Carbon, Fergus, and Judith Basin Counties (fig. 28). For the two larger API sizes associated with samples A06-1(40/70) and B65-6 (20/40), the samples contained both clustered material and abundant lithic fragments. Sample A19-1 had an API size of 70/140 and passed both sphericity and roundness tests with values of 0.670 and 0.672, respectively. However, over 25% of fines were produced from crush testing at 5,000 psi. The high percentage suggests these Morrison Formation outcrops do not contain potential proppant.

Blackleaf Formation: Flood Member (Lower Cretaceous)

Eight samples were collected from the Flood Member of the Blackleaf Formation (fig. 28). The material was difficult to completely disaggregate, initially resulting in erroneously large, mean size based on the clusters contained in the processed sample.

After complete disaggregation none of the samples passed the minimum requirements, primarily due to low sphericity and roundness. The samples with fine to very fine grain size (i.e., API sieve sizes of 70/140) exhibited sphericity and roundness values below the minimum requirements for further testing. Sample LIMA-10 met the sphericity and roundness requirements; however, it failed crush tests at both 6,000 and 5,000 psi, producing 12.4% and 12.1% fines, respectively. LIMA-10, CFD-10, and ELL-04 are the only samples from the Blackleaf Formation that exhibit API mesh sizes of 70/140. The remainder of the samples contained smaller grains.

Virgelle Formation (Upper Cretaceous)

Twenty-six samples were collected throughout north-central Montana from the Virgelle Formation (fig. 28). All of the samples failed to meet minimum standards for proppant. The API sieve size for the Virgelle samples ranges from 20/40 down to 70/140. Twenty of the samples failed due to inadequate sphericity and roundness, the presence of clusters, and/or insufficient silica content. The remaining six samples failed crush tests at 5,000 psi. Based on these samples, the Virgelle Formation in Montana does not appear to be a viable source of proppant.

Phosphoria Formation (Permian)

Four samples from the Phosphoria Formation (DNRC-TK-01 through 04) were collected in Beaverhead County in southwestern Montana. The sampler's notes describe the DNRC-TK-01 samples as "hi silica cemented, pink, medium to coarse grain size." The sampler noted that DNRC-TK-04 "didn't scratch with a knife."

In the lab, these samples were found to be extremely well cemented, making separation of the individual grains impossible. Testing of these samples was not conducted.

Tertiary Gravels

Samples from Tertiary gravels were collected in several locations (fig. 28) in northeastern Montana (Valley, Roosevelt, and Daniels Counties). In general these samples contained significant amounts of non-silica lithic clasts and performed poorly in the laboratory tests. These samples included A39-2, A40-4, A41-1, and A45-1, among others. The micrograph of the 60 mesh retrieval for sample A40-4 (fig. 38) is typical of these materials.

CONCLUSIONS

Of the formations discussed in this paper, the Tyler Formation showed the most promising results based on laboratory tests. Outcrops in the northeastern part of the Little Belt Mountains and the northeastern part of the Big Snowy Mountains produced material that met and surpassed minimum criteria for proppant. However, the Tyler sandstone units are generally thin, and this may limit its viability.

Samples from the Quadrant Formation in the northeastern part of the Little Belt Mountains and in southwestern Montana near Dillon and Lima also met the minimum requirements for proppant.

The Tensleep Formation (lateral equivalent of the Quadrant of western Montana) shows potential in the dune sandstone component that is interbedded with massive marine sandstones in the southern part of Montana, particularly in Carbon County.

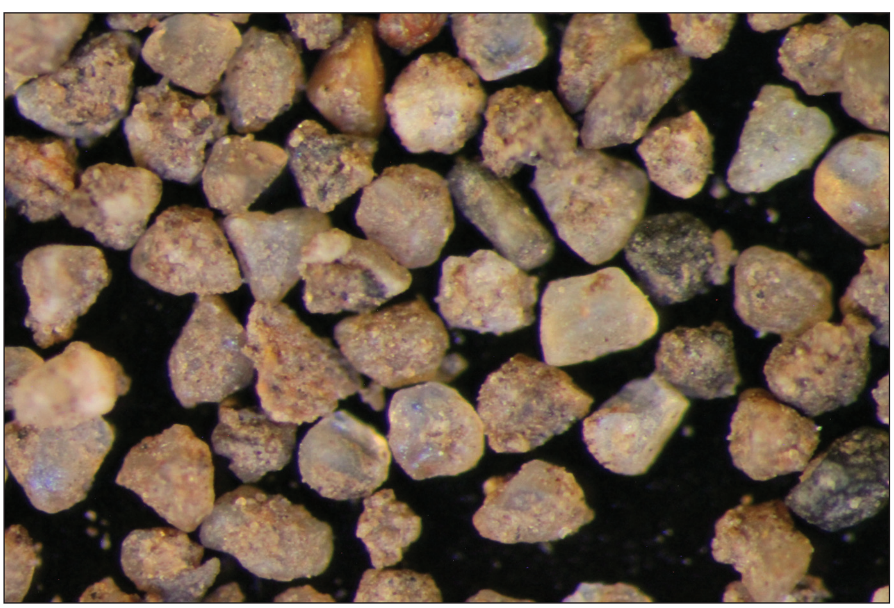


Figure 38. Microscopic view—Tertiary gravel. Sample A40-4, 60 mesh retrieval shows the mixed lithologies common to these samples.

The Sunburst member of the Kootenai Formation, sampled near Great Falls, produced results that met the minimum criteria for proppant.

Samples from the Flathead Formation produced test results that indicate some potentially viable proppant on the south side of the Little Belt Mountains.

Two samples of eolian dune deposits in northeastern Montana met minimum requirements for proppant.

The northeastern flank of the Little Belt Mountains had the greatest concentration of formations that met the minimum requirements for proppant material, including the Kootenai, Quadrant, Tyler, and Kibbey Formations.

Data from this study are available on the Montana Bureau of Mines and Geology website: http://data.mbmg.mtech.edu/proppant/data.asp. This database may also include corrections and updates not reflected in this report.

ACKNOWLEDGMENTS

The principal investigators on this project are indebted to a range of people and organizations who have helped make this project a success. Our appreciation especially goes to the Montana Board of Oil and Gas Conservation for their significant financial support and encouragement of this project and to State Senator Jim Keane, for his interest in our work. Gratitude is extended to the Petroleum Engineering Department at Montana Tech for the use of their laboratory space.

Contributors from the Montana Bureau of Mines and Geology include Richard Berg, Senior Research Geologist (retired): study design assistance; Susan Vuke, Senior Research Geologist (retired): identification of target sandstones, geologic field maps, sampling, review; Luke Buckley, Data Systems Manager: design and maintenance of the database and the web interface; Jay Gunderson, Senior Research Geologist: sampling, editing; David Lopez, Senior Research Geologist (retired): field expertise and guidance with Tensleep Formation and Greybull Member of Kootenai Formation in south-central Montana; Tom Patton, Research Division Chief and Senior Research Hydrogeologist (retired): overall support and guidance.

Montana Tech Student Contributors include Timothy Denton, BS Petroleum Engineering (2014); Chris Bulau, BS Petroleum Engineering (2014); Alec Shull, BS Petroleum Engineering (2015); Alicia Kastelitz, BS Petroleum Engineering (2015); Natalia Krzywosz, MS Geoscience, Geophysical Engineering (2015); Igor Koracin, MS Petroleum Engineering, (2015); Rachael Wilford, BS Petroleum Engineering (2017); Zack Stevens, BS Petroleum Engineering (2017); Jonathan Rice, BS Geophysical Engineering (2018); Collin Ireland, BS Petroleum Engineering (2018).

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APPENDIX A:
WENTWORTH GRAIN SIZE TABLE

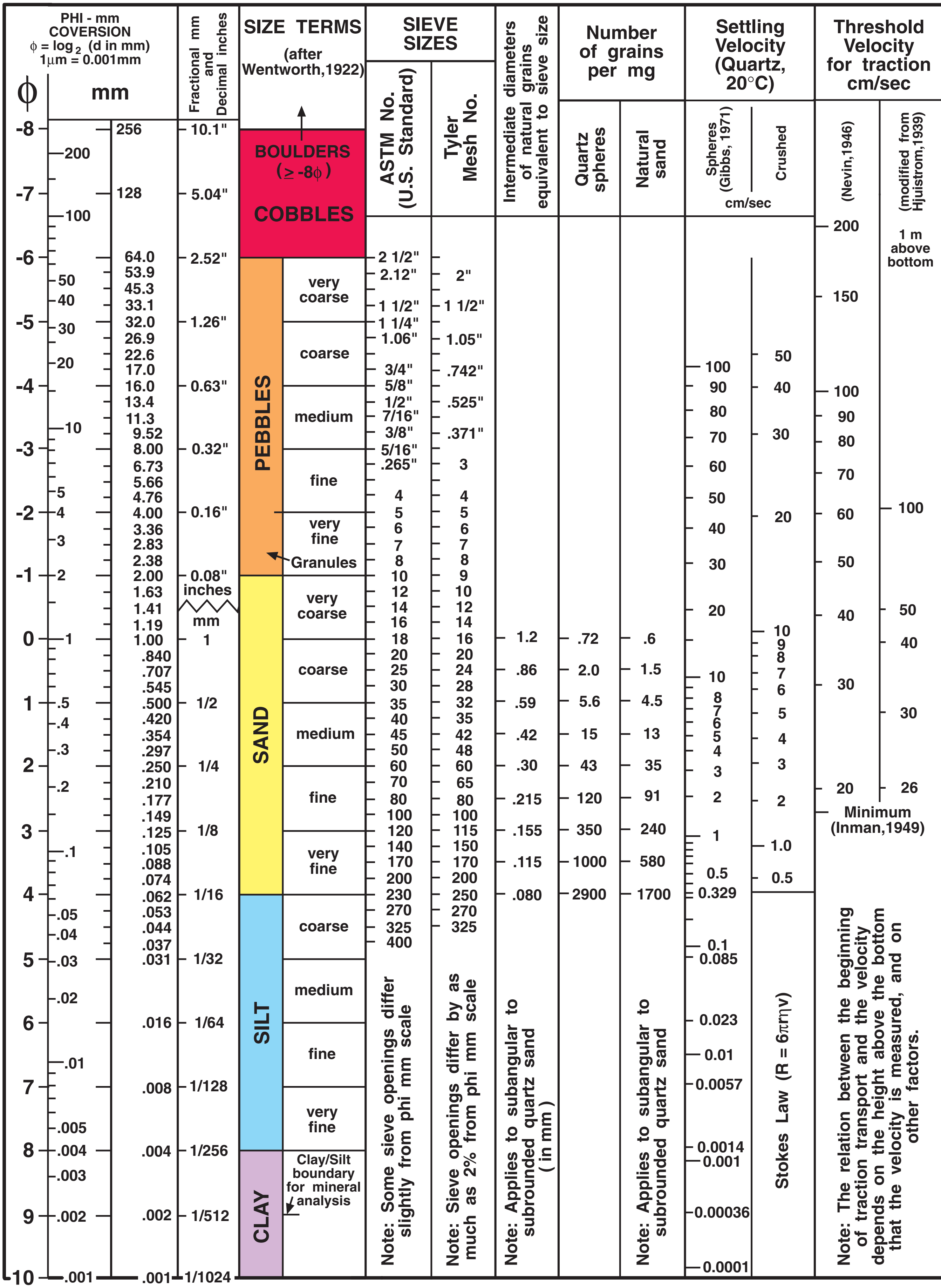

Figure A1. Wentworth grain size chart, USGS. Available at http://pubs.usgs.gov/of/2003/of03-001/htmldocs/images/chart.pdf.

APPENDIX B:

SNAP FIELD SAMPLING FORM

SNaP	**Field Data Collection Form for Grab Samples**	SID (MBMG Only)	
Sample # *		**Name of Sampler ***	
Date *		**Email**	
GPS		**Formation Information**	
LAT (decimal)		**Formation Name**	
LONG (decimal)		**Thickness**	
Elevation (ft)		**Exposed**	
		Unit	
Township		**Extent**	
Range		**Pictures**	
Section		**How many ***	
County		**Picture Numbers ***	
QuadrangleName			**1:100,000**
QuadrangleName			**7.5'**
Sample Characteristics			
Color			
Grain Shape			
Reaction to Acid			

Instructions

Complete as many fields as possible. Except for those cells marked with *, you may leave it blank

In order to process the samples, a data collection form should be submitted for each sample

Provide Lat and Long in decimal degrees, (eg 46.7890123), Date is when the sample was collected

Please email pictures of the sample location to proppantresearch@mtech.edu

If you want results on your sample, please include your email address

Data collected becomes the property of Montana Tech and will be made available to the general public

APPENDIX C:

MEASURED SECTIONS REFERENCES AND NOTES

Appendix C: Measured Sections References and Notes

Additional information on these sections is available here: http://data.mbmg.mtech.edu/proppant/Data.asp?pageview=MS&

Reference	Notes
Alexander, R.G., Jr., 1955, Geology of the Whitehall area, Montana: Yellowstone-Bighorn Research Project Contribution no. 95, 110 p.	
Austin, W.H., Jr., 1950, Reconnaissance geology of the south flank of Cinnamon Mountain, Gallatin County, Montana: Ann Arbor, University of Michigan, M.S. thesis, 102 p.	
Bierwagen, E.E., 1964, Geology of the Black Mountain area Lewis and Clark, and Powell Counties, Montana: Princeton University, Ph.D. dissertation, 46 p.	
Childers, M.O., 1960, Structure and stratigraphy of the southwest Marias Pass area, Flathead County, Montana: Princeton University, Ph.D. dissertation, 181 p.	
Christie, H.H., 1961, Geology of the southern part of the Gravelly Range, southwestern Montana: Corvallis, Oregon State College, M.S. thesis, 159 p.	
Cobban, W.E., Erdmann, C.E., Lemke, R.W., and Maughan, E.K., 1976, Type sections and stratigraphy of the members of the Blackleaf and Marias River Formations (Cretaceous) of the Sweetgrass Arch, Montana: U.S. Geological Survey Professional Paper 974, 66 p.	
Deiss, C., 1936, Revision of type Cambrian Formations and sections of Montana and Yellowstone National Park: Geological Society of America Bulletin v. 47, p. 1257-1342.	

Reference	Notes
Deiss, C.F., 1939, Cambrian stratigraphy and trilobites of northwestern Montana: Geological Society of America Special Paper no. 18, 135 p.	
Dutro, T.J., 1979, Carboniferous of the northern Rocky Mountains, Big Snowy Mountains Region, Montana: AGI Selected Guidebook Series no. 3, p. 28.	
Easton, W.H., 1962, Carboniferous formations and faunas of central Montana: U.S. Geological Survey Professional Paper 348, 126 p.	Reference has detailed descriptions at the beginning of each section on how to get to the specific sites.
Gardner, L.S., 1959, Revision of the Big Snowy Group in central Montana: American Association of Petroleum Geologists, v. 43, no. 2, p. 329-349.	
Gill, J.R., and Burkholder, R.E., 1979, Measured sections of the Montana Group and equivalent rocks from Montana and Wyoming: U.S. Geological Survey Open-File Report 79-1143, 203 p.	
Glasheen, R.M., 1969, Geology of the Whetstone Ridge area, Meagher County, Montana: Corvallis, Oregon State University, M.S. thesis, 137 p.	Reference has information on the Judith River and Lennep formations. None of the sandstone units appear promising because of either high lithic or feldspar content.
Goers, J.W., 1964, Geology and groundwater resources of the Stockett-Smith River area, Montana:,Missoula, University of Montana, M.S. thesis, 123 p.	Sandstones of the Kibbey Formation in this area are friable and poorly indurated (p. 30).
Hall, W.B., 1961, Geology of part of the Upper Gallatin Valley of southwestern Montana: Laramie, University of Wyoming, Ph.D. dissertation, 239 p.	

Reference	Notes
Hanson, A.M.,1952, Cambrian stratigraphy in southwestern Montana: Montana Bureau of Mines and Geology Memoir 33, p. 25-41.	Typically, the lower part of the Flathead Formation has more potential than higher in the section where there is usually sandstone interbedded with shale and more clay present. Also farther north and west showed more promise than the south and eastern sections discussed in this paper.
Harris, W.L., 1972, Upper Mississippian and Pennsylvanian sediments of Central Montana: Missoula, University of Montana, Ph.D. dissertation, p. 1-58, 75-92, 110-112, 173-191, 241-248.	Sandstones of the upper Kibbey are fine to very fine grained (0.2- 0.05 mm). Coarse-grained sandstones are present on the northern side of the Little Belt Mountains and to the east. Larger grains are typically rounded to well-rounded and smaller grains are angular. Mostly moderately to well sorted. Friable because of incomplete calcareous cementation. The uppermost unit of the Quadrant is well indurated because of almost complete siliceous cementation.
Key, C.F., 1987, Stratigraphy and depositional history of the Amsden and lower Quadrant Formations, Snowcrest Range, Beaverhead and Madison Counties, Montana: Corvallis, Oregon State University, M.S. thesis, 187 p.	
Klepper, M.R., Ruppel, E.T., Freeman, V.L., and Weeks, R.A., 1971, Geology and mineral deposits, east flank of the Elkhorn Mountains, Broadwater County, Montana: U.S. Geological Survey Professional Paper 665, 66 p.	

Reference	Notes
Knappen, R.S., and Moulton, G.F., 1930, Geology and mineral resources of parts of Carbon, Big Horn, Yellowstone, and Stillwater Counties, Montana: U.S. Geological Survey Bulletin 822-A, 70 p.	On page 37 there is information about the Eagle Sandstone, however it is not very descriptive. Much of the sandstone is interbedded with shale, clay, or coal. The Greybull Member is mentioned on page 26 but has no sandstone in its measured section. The Greybull is defined as a resistant sandstone with limonite cement with grain size less than 0.4mm. It has a high clay content.
Loen, J.S., 1990, Lode and placer gold deposits in the Ophir district, Powell, and Lewis Clark Counties, Montana: Colorado State University, Ph.D. dissertation, 264 p.	
Lopez, D.A., and VanDelinder, S.W. 2007, Measured sections of the Pennsylvanian Tensleep Sandstone, Pryor and Bighorn Mountains, Montana: Montana Bureau of Mines and Geology Open-File Report 553, 55 p.	The lower 29 ft of the formation not included in the database has many thin layers, all composed of limy sandstone with calcareous matrix, They all have fine to very fine grain size and much cross bedding with parallel laminated section typical towards the bottom of this section. There is also a 1 ft section of siliceous sandstone followed by siltstone at the base of the "top lower Tensleep". The Amsden Formation underlies all of the above Tensleep formations from this reference.
Mahorney, J.R., 1956, Geology of the Garrity Hill area, Deer Lodge County, Montana: Bloomington, Indiana University, M.A. thesis, 40 p.	The Quadrant section was not measured because of an excessive amount of Quadrant talus and cover.
Mann, J.A., 1954, Geology of part of the Gravelly Range, Montana: Yellowstone-Bighorn Research Project Contribution no. 190, p. 75-92.	

Reference	Notes
Maughan, E.K., and Roberts, A.E., 1967, Big Snowy and Amsden Groups and the Mississippian-Pennsylvanian boundary in Montana: U.S. Geological Survey Professional Paper 554-B, 27 p.	Reference describes the increasingly sandy trend towards the west for the Devil's Pocket Formation (p. B16). Also many of the sections have specific directions to outcrop sites and also span across more than one location. The first, or most specific, of the locations provided for each measured section is provided.
McGill, G.E., 1958, Geology of the northwest flank of the Flint Creek Range, western Montana: Princeton University, Ph.D. dissertation, 193 p.	The Flathead, Shedhorn, and Quadrant are described as relatively hard, pure quartzites. The Flathead is described as a first or second quality glass sand. It is not included in the database because tightly cemented, but is located in NE 1/4, SW1/4, sec. 27, T. 09 N., R. 13 W. (p. 161).
McKelvey, V.E., 1959, The Phosphoria, Park City, and Shedhorn Formations in the Western Phosphate field: U.S. Geological Survey Professional Paper 313-A, 45 p.	
McLane, M.J., 1971, Phanerozoic detrital rocks at the north end of the Tobacco Root Mountains, southwestern Montana: a vertical profile: Bloomington, Indiana University, Ph.D. dissertation, 253 p.	Reference includes detailed information about each unit except for thickness that was estimated for each unit from drawn stratigraphic sections.
McMannis, W.J., 1952, Geology of the Bridger Range area, Montana: Princeton University, Ph.D. dissertation, 47 p.	

Reference	Notes
Mertie, J.B., 1951, Geology of the Canyon Ferry quadrangle, Montana: U.S. Geological Survey Bulletin 972, 95 p.	Reference does not contain any measured sections but describes the Flathead and the Quadrant Formations. Flathead (p. 21): brittle unit displaced by numerous small cross faults producing step-like outcrops. NW of Hellgate Gulch the Flathead is tightly folded and bent with little evidence of rupturing. It contains mostly medium to coarse quartzite grains and mostly pale gray with occasional purple and red banding. Quadrant Formation (p.28): Exposed along the front of the Big Belt Mountains in the vicinity of White Gulch and at places in the southeastern part of Spokane Hills. This formation consists of quartzite interbedded with limestone, sandstone, and shale. The quartzite is hard, tough, brittle and vitreous. The sandstone is thin-bedded and brown, red, or gray; most is soft and shaly, but some is quartzitic and other is calcareous.
Moberly, R.M., 1956, Mesozoic Morrison, Cloverly, and Crooked Creek Formations, Bighorn Basin, Wyoming and Montana: Princeton University, Ph.D. dissertation, 47 p.	There are some promising quartz arenites in the Cloverly Formation in Wyoming. They are medium- to fine-grained, friable, calcareous and sparkly. (sec. 19, T. 57 N., R. 94 W.)
Mudge, M.R., 1972, Pre-Quaternary rocks in the Run River Canyon area, northwestern Montana: U.S. Geological Survey Professional Paper 663-A, 142 p.	Measured sections of the Blackleaf Formation, Flood Member are on p. 26. The Flood contains many layers of sandstone and it is all noncalcareous, mostly composed of quartz, feldspar, and chert. Each section is very fine grained. Also most of it is interbedded with shale and contains granules of claystone.

Reference	Notes
Nave, F.R., 1952, Geology of a portion of the Bridger Range, Montana: Iowa City, State University of Iowa, M.S. thesis, 104 p.	
Richards, P.W., 1955, Geology of the Bighorn Canyon - Hardin area, Montana and Wyoming: U.S. Geological Survey Bulletin 1026, 93 p.	
Richards, P.W., 1957, Geology of the area east and southeast of Livingston, Park County, Montana: U.S. Geological Survey Bulletin 1021-L, p. 385-436.	There is information in this reference about the Virgelle Formation (p. 417-419) but it does not indicate any specific locations for sandstone, nor does it describe its characteristics in any detail other than color and weathering.
Robinson, G. D., 1963, Geology of the Three Forks Quadrangle Montana: U.S. Geological Survey Professional Paper 370, 143 p.	
Rose, R.R., 1967, Stratigraphy and structure of part of the southern Madison Range, Madison and Gallatin Counties Montana: Corvallis, Oregon State University, M.S. thesis, 172 p.	
Theodosis, S.D., 1956, The geology of the Melrose area, Beaverhead and Silver Bow Counties, Montana: Bloomington, Indiana University, Ph.D. dissertation, 118 p.	The uppermost Quadrant at one location is described as friable (p. 42). NW1/4, sec. 30, T. 01 S., R. 09 W., and NW1/4 sec. 13, T. 01 S., R. 09 W.,sec.13, NW. Elsewhere in the Melrose area, the Quadrant is tightly cemented.
Tysdal, R.G., 1970, Geology of the north end of the Ruby Range, southwestern Montana: Missoula, University of Montana, Ph.D. dissertation, p. 133-180.	
Vine, J.D., 1956, Geology of the Stanford-Hobson area, central Montana: U.S. Geological Survey Bulletin 1027-J, p. 405-467.	Page 416 contains well log information which describes the Kibbey Formation as sandstones that are typically very fine grained to silty but there is one 15 ft

Reference	Notes
	section containing white, fine to medium grained sandstone.
Weed, W.H., 1900, Geology of the Little Belt Mountains, Montana: U.S. Geological Survey Annual Report no. 20, 1899-99, pt. 3, p. 284-318.	
Wilson, M.D., 1970, Cretaceous stratigraphy of the southern Madison and Gallatin Ranges, southwestern Montana: University of Idaho, Ph.D. dissertation, 55 p.	
Witkind, I.J., 1969, Geology of the Tepee Creek quadrangle Montana-Wyoming: U.S. Geological Survey Professional Paper 609, 101 p.	