Subsurface to Surface Correlation of the Tensleep Sandstone in the West Flank of the Pryor Mountains in Carbon County, Montana

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Subsurface to Surface Correlation of the Tensleep Sandstone in the West Flank of the Pryor Mountains in Carbon County, Montana

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A Non-thesis Research Paper submitted in partial fulfillment of the requirements for:

Master of Science Degree
Geoscience: Geology Option

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May 12, 2014

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Abstract

The Pennsylvanian Tensleep Sandstone is an eolian and nearshore marine/sabka quartz arenite unit with prominent outcrops along the western Pryor/Bighorn Mountain front east of Red Lodge, MT. Regionally, the formation represents one of the largest ergs in the global geologic record. High permeability makes it an important oil and gas reservoir and aquifer in south central Montana and throughout much of Wyoming. The Tensleep Sandstone’s high percentage of quartz content and grain roundness, due to its eolian origin, makes it a prospective source for natural proppant sand.

Three continuous 4-inch cores were obtained during a cooperative project between Montana Tech and industry partners. Using stratigraphic sections, cores, thin sections, and x-ray fluorescence (XRF) analysis, the usefulness and economic feasibility of the Tensleep Sandstone as a minable hydraulic fracture proppant was explored. Usefulness depends on cementation, grain shape, grain size, and depth from surface of the prospective zone. Grain shape and size were determined by thin sections, sieving, and stereomicroscope analysis. Analysis of 20 disaggregated sand samples has shown that as much as 30 percent of the grain sizes fall between 30-50 mesh (medium- to fine-grained sand size) and about 45 percent of the grain sizes fall between 70–140 mesh (very fine-grained sand to coarse silt), grain sizes appropriate for some hydraulic fracture operations. Core descriptions and XRF data display the distribution of lithology and cementation. Elemental (XRF) analyses help to delineate more pure quartz sands from those with grain fractions reflecting fine-grained clastic and evaporitic inputs. The core and nearby stratigraphic sections are used to quantify the amount of overburden and the
amount of resource in the area. Initial results show favorable crush strength and useable grain size and shape.

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Introduction

The Tensleep Sandstone in Central Montana has been of interest to various industries throughout the last century for its high percentage of quartz and ease of access for mining. In South Central Montana (Figure 1), the Tensleep Sandstone is being investigated as a possible source for sand-sized hydraulic fracture proppant for oil and gas well completions. Three cores were drilled in the study area and 10 samples were taken from each core. Initial tests were done in the Proppant Research Division in the Petroleum Engineering Department at Montana Tech of the University of Montana. The geologic study involved using a portable X-ray Fluorescence (XRF) machine to gather elemental analysis of each core, thin section descriptions, core descriptions, and the surface stratigraphic sections described by Lopez et al. (2007), to create stratigraphic columns to establish the boundary between the informal upper and lower Tensleep Sandstone members.

All data in this report were collected on the east flank of the Pryor Mountains of South Central Montana, roughly 6 miles north of the Wyoming - Montana border (Figure 1).
**Geologic History**

The Pennsylvanian Tensleep Sandstone is a regionally important hydrocarbon reservoir in Montana and Wyoming. The Tensleep Sandstone is part of the Wyoming shelf lithologic province and is the equivalent of the Quadrant Quartzite in the extreme northwestern part of Wyoming and the Weber Sandstone in northeastern Utah (Mallory, 1973). The Tensleep Sandstone was originally described in Big Horn County, Wyoming in 1904 by Darton.

In the study area, the Tensleep Sandstone has been informally broken into an upper and lower section and is overlain by the Phosphoria Formation and underlain by the Amsden Formation (Figure 2). The lower member is characterized by repeated cycles of marine sandstone capped by calcareous sandstone beds. The upper Tensleep Sandstone member is characterized by cycles of eolian dune sandstone capped by marine calcareous sandstone (Lopez et al., 2007).
Figure 1 - Location map of study area in south central Montana (shown in red box).
Figure 2 - General Stratigraphic section for Pennsylvanian and Mississippian Age in Montana Modified from Vuke et al. (2007).
Figure 3 - Geologic map of project area (outlined in black box). Modified from Lopez (2000).
**Procedures/Methods**

Three continuous 4-inch cores were obtained by air-rotary drilling with a water-well drilling rig in the study area. The locations of the cores were chosen strategically to get core of the complete Tensleep Sandstone; the first location was chosen to capture the top of the Tensleep Sandstone (SS-1). The other two cores (SS-5, SS-11) were chosen to capture the lower sections of the Tensleep Sandstone, to a depth of over 180’. The first core (SS-1) was cut in ¼ SW ¼ SW ¼ SW, Section 32, T8S., R26E. The second core (SS-5) was cut in ¼ SE ¼ NW ¼ SE, Section 31, T8S., R26E. The third core (SS-11) was cut in ¼ NW ¼ SW ¼ SW, Section 4, T9S., R26E (Figure 4).

Lopez et al. (2007) measured two surface sections in or near the study area through the Tensleep Sandstone. The Stockman Trail section is located near drill site SS-5 at SW ¼ Section 32 T8S R26E and the Bear Canyon section is located east of drill site SS-11 at SE ¼ SW ¼ Section 3 T9S R26E. Descriptive data were presented in tabular form and are summarized here to create grain size and lithology logs to provide a better overview of the Tensleep. The distinction between the informal upper and lower Tensleep was especially important in understanding the geologic significance of the contact (Lopez et al., 2007). The grain sizes described in the outcrop sections ranged from very fine to fine sand, and lithology and sedimentary structures were recorded (Lopez et al., 2007).

Ten samples were taken from each core at depths that appeared promising as proppant material. Jim Gruber and Dr. Larry Smith sat on the coring rig to describe the core as it was drilled. The core was then boxed up, labeled, and sent to Montana Tech of the University of Montana, where further work was completed.
1. Core description

Some core descriptions were done on site during the drilling process. Where coring became very slow due to higher induration of rocks, rotary drilling was used with the collection of cuttings used for description. Rock type, cementation, grain size, reaction to dilute HCl, burrowing features, color of the rock, bedding features, and a general description of each section was completed for each core. Core descriptions were completed in labs at Montana Tech of The University of Montana. See Appendix A for the original core descriptions. Based on initial core description, 10 representative samples of sandstones were chosen for proppant and thin section sample preparation.

2. Crush testing

Crush testing was conducted in the Proppant Research Division of the Petroleum Engineering department at Montana Tech of the University of Montana. Methods used for crush testing follow ISO 13503-2:2006 Part 2 specifications. Samples were disaggregated by mortar and pestle and washed in a weak acid. Samples were tested at a pressure of 5000psi. The test was done on a subsample of the rock between the #70 and #140 size meshes. The percentage of rock that was crushed at 5000psi was measured to indicate bulk grain strength. Samples with an increased amount of finer-grained material after crushing suggest lower strengths. The full crush testing dataset is available in Appendix B.

3. Sieve Tests

Sieving was conducted in the Proppant Research Division of the Petroleum Engineering department at Montana Tech of the University of Montana. Sieving was
done on the 10 samples taken from SS-1 and SS-5. Methods for sieving follow ISO 13503-2:2006 Part 2 specifications. Sieve sizes used were ASTM #16, #20, #30, #40, #50, #60, #70, and #140. All grains smaller than the #140 mesh fell into the pan. The full sieve dataset is available in Appendix B.

4. XRF

A hand-held Niton Prospect X-Ray Fluorescence (XRF) machine was used to create elemental analyses of each core. The XRF machine was operated in “Test-All Geo” mode with 80 second scans. Standard soil samples of known composition were analyzed before and after all data were taken to check instrument calibration. An XRF reading was taken at every foot of available core. Some footage was missing from each core where drilling complications required coring to be suspended and the rock needed to be drilled through. In some places the rock was too soft or unconsolidated for full core recovery. Each foot of core was visually inspected and the XRF reading was taken at a point that best represented the foot of core. The data were then imported into Microsoft Excel and graphed to find possible elemental relationships that could help with correlation of stratigraphic markers between the cores.

5. Microscopic analysis

5.1. Petrographic

At each interval subjected to crush and sieve testing, a sample was cut for making a thin section. 30 sandstone thin sections were prepared by Texas Petrographic Service Inc., or Quality Thin Sections, Inc. All thin sections were stained with alizarin red which helps to distinguish dolomite from calcite. Thin sections for core SS-1 and core SS-5 had
cover slides permanently attached for ease of use under a microscope and to decrease issues with air bubbles trapped under cover slide interfering with visual identification of key attributes. The depth of where each sample was taken is designated in Appendix A in the core logs.

A Meiji ML 2000 microscope with 4x, 10x, and 40x lenses was used. Each thin section was inspected for mineral identification of the mineral grains and cementation between grains. Grain shape was noted and compared to a roundness chart (Powers, 1953) for accurate identification and grain size was qualitatively analyzed.

5.2. Binocular

Analysis with a binocular microscope was done by staff in the Proppant Research Division to get an estimate of the sphericity and roundness of the grains present in each sample. This analysis was done after sieving, using only grains between the #70 mesh and the #140 mesh. The full dataset is located in Appendix B.

6. Modal Mineralogy

Two samples from Sample 2 of core SS-11 (36’) were analyzed by the Center for Advanced Mineral and Metallurgical Processing (CAMP) at Montana Tech of the University of Montana using Mineral Liberation Analysis (MLA). MLA is done by a scanning electron microscope equipped with energy dispersive X-ray spectrometers with software that automates the operation of the microscope (Sylvester, 2012). MLA gives a thorough quantitative analysis of modal mineralogy by classifying the X-ray spectra of mineral species by comparison to a library of reference spectra.
Results

1. Stratigraphic Sections

Stratigraphic sections were created for each core using the core descriptions gathered by Jim Gruber and Dr. Larry Smith (Figure 5 to Figure 9). Stratigraphic sections were also created by the author for the Stockman Trail and Bear Canyon surface sections described by Lopez et al. (2007). All stratigraphic sections were drawn to the same scale as the sections from Lopez et al. (2007) (Figure 4). Data of grain size, lithology and sedimentary structures are shown on the stratigraphic sections derived from the core and surface sections were included. Rock type, grain size and sedimentary structures were compiled on the stratigraphic sections to look for continuous stratigraphic attributes between the cores. The range of sand grain sizes present was very fine upper, fine upper, fine lower, medium lower, and medium upper (Wentworth, 1922). The stratigraphic sections are discussed from northwest to southeast.
Figure 4 - Core locations and measured sections with the cross section outline
1.1. SS-5 Stratigraphic Section

The SS-5 drill site is the farthest east of all the locations. Core recovery at SS-5 started at 15’ below ground level, and was completed at 135’. There is a four foot thick limestone at 26’, and then the core is sandstone down to 108’. Tabular crossbeds are present between 80’ and 85’ and chert nodules are recorded between 87’ and 88’. More tabular cross bedding occurs from 88’ to 95’. Limey sandstone and sandy limestone with some silt layers is present from 100’ to 116’. Sandstone with no bedding features is seen from 116’ to 129’ with two 1’ limestone layers at 123’ and 127’. The core was completed in a clay mudstone that was 5 feet thick at Total Depth (TD) (Figure 5).
Figure 5 - SS-5 Stratigraphic section, grain size chart, and crush test chart. S1 to S10 show depth of samples subject to proppant testing and thin section analysis
1.2. SS-1 Stratigraphic Section

Core SS-1 is the second most eastern drilling location. The stratigraphic section of core SS-1 is 150’ long; recovery began 2’ below ground surface. There is a 2’ limestone from 11 to 13 feet, and then sandstone is present until 64’. That 50’ section of sandstone is fairly homogenous, with little change in grain size, but there is crossbedding visible from 30’ to 55’. A prominent limestone bed is seen from 64’ to 74’. The top 4’ of this limestone has chert nodules present, and the lower 6’ of the limestone is homogenous. Sandstone with no bedding features is seen from 74’ to 83’. Between 83’ and 84’ is siltstone, then sandstone to 85’. A one foot limestone layer is seen at 85’. Sandstone is from 86’ to 89’ then the core is limestone until 90’, where it becomes sandstone from 90’ to 95’. Limestone is present from 95’ to 97’. Directly below that limestone is sandstone that extends to 116’. A foot of limestone then a foot of sandstone is seen before a cherty dolomite at 118’. Below the dolomite is a foot of siltstone until 121’. Sandstone extends from 121’ to 125’, where the core becomes limestone for one foot. A thin layer of siltstone is from 126’ to 127’. Limestone extends from 127’ to 130’. The rest of the core to TD is sandstone, with tabular crossbeds occurring from 147’ to 150’ (Figure 6).
Figure 6 - SS-1 Stratigraphic section, grain size chart, and crush test chart. S1 to S10 show depth of samples subject to proppant testing and thin section analysis.
1.3. **Stockman Trail Stratigraphic Section**

The Stockman Trail stratigraphic section was created using data from Lopez et al. (2007), surface description of the Tensleep Sandstone. This stratigraphic section catalogues the complete Tensleep Sandstone, which is 186’ thick at this location. Sandstone constitutes the top 67’ of the stratigraphic section, with high angle trough crossbeds seen between 25’ and 35’. From 67’ to 73’, limestone is present. Between 73’ and 85’ is a sandstone with high angle trough crossbeds. From 85’ to 89’ is a dolomitic, cherty limestone. In the large sandstone section from 89’ to 172’, crossbedding is abundant. Tabular cross beds are present from 93’ to 97’. At 118’, more tabular crossbeds are seen. Trough cross beds occur again between 123’ and 125’. From 136’ to 138’, tabular crossbeds exist and trough crossbeds are seen at 150’. The sandstone at 166’ shows tabular crossbeds. A thin mudstone is present 172’ to 174’. The base of the Tensleep Sandstone on the Stockman Trail stratigraphic section is composed of 12’ of sandstone with climbing ripples and overlies the Amsden Formation (Figure 7).
Figure 7 - Stockman Trail stratigraphic section, built using surface section descriptions from Lopez et al. (2007).
1.4. **SS-11 Stratigraphic Section**

The stratigraphic section for the SS-11 core is 120’ long. Core recovery began at 12’ below ground surface. Sandstone extends from the start of the core to a depth of 43’. At 43’, a 5’ thick layer of thinly bedded limestone and sandstone was recovered. From a depth of 48’ to 119’ the interval is sandstone. From 48’ to 53’ there are no bedding features. From 53’ to 67’, the sandstone displays tabular crossbeds. From 67’ to 83’ no bedding features are evident. A 3’ section with tabular crossbedding starts at 83’ and ends at 86’. After that thick section of sandstone, another thinly bedded limestone and sandstone layer is present from 119’ to 122’. Sandstone extends from 122’ to TD of 132’. There was no crush testing or sieve testing done for this core.
Figure 8 - SS-11 Stratigraphic section and crush test chart. S1 to S10 show depth of samples subject to proppant testing and thin section analysis.
1.5. **Bear Canyon Stratigraphic Section**

The Bear Canyon stratigraphic section was created using Lopez et al. (2007) surface description of the Tensleep Sandstone. This stratigraphic section catalogues the complete Tensleep Sandstone, which is 197’ thick at this location. The uppermost 5’ are dolomite. A sandstone with trough cross beds is seen from 5’ to 15’. At 15 feet, another dolomite is present, this time 5’ thick, ending at 20’. From 20’ to 70’ is a sandstone with high angle trough crossbeds. A calcareous layer is present from 70’ to 90’. The first 18’ of this layer is dolomite, with a 2’ limestone completing the layer. The top of this thick calcareous layer marks the base of the upper Tensleep Sandstone, according to Lopez et al. (2007). Below the limestone layer is sandstone that extends to the base of the stratigraphic column. From 85’ to 95’, low-angle tabular crossbedding is present, then again from 105’ to 110’. There are no bedding features from 110’ to 132’. Low-angle trough crossbeds occur again from 132’ to 135’. The next bedding feature, ripple cross laminations, appears from 152’ to 155’. From 156’ to 180’, there are no bedding features. The last bedding features seen in this section are between 178 feet and 188 feet. The basal Tensleep Sandstone in this stratigraphic section ends with a sandstone that has no bedding features (Figure 9).
Figure 9 - Bear Canyon Stratigraphic section
2. Crush Testing

When conducting a crush test on possible fracture proppant, less than 10% of the rock should fracture at the given pressure. At 10% on all graphs of the crush test data is a ‘failure line’ showing where samples are unusable and where the rock is potentially strong enough to be used as proppant. All samples for this project were tested using 5,000 psi. Crush data indicate a low crush percentage rock layer in the lower Tensleep in all the cores that is roughly 10 feet thick. Sample 4 (58’) of SS-5 shows a favorable crush percentage of under 10% (Figure 5). Sample 8 (111’) and Sample 9 (138’) of SS-1 have a low crush percentage as well (Figure 6). Sample 7 (110’) of SS-11 also has a low crush percentage. All of these samples are in the lower Tensleep Sandstone.

SS-1 and SS-11 both have a thin layer of low crush percentage rock very close to the base of the upper Tensleep Sandstone contact, but it wasn’t seen in the SS-5 core, possibly because it was stratigraphically above where the core began. The complete dataset for the crush test is in Appendix B.

3. Sieving

The majority of the rock samples were larger than the #140 mesh, which is the cutoff for possible hydraulic fracture proppant. Grains smaller than #140 are generally not used for proppant. All samples from SS-5 have over 50% of grains larger than the #140 mesh. The lowest percentage sample was Sample 7 (90’), with only 67% of the grains larger than #140. Where the crush test shows a low crush percentage section in the lower Tensleep Sandstone (Sample 4, 58’), the sieve test shows 79.5% of the rock with favorable grain size. Sample 5 (69’) of SS-5 is also below 10% crushed rock and the
sieve test for that same sample indicates that 90.5% of the grains are larger than #140 mesh.

SS-1 has much more variability in grain size. In the lower Tensleep Sandstone member where the crush test indicated less than 10% crushed grains, Sample 8 (111’) has 66.7% of the rock is larger than #140. Sample 9 (138’) of SS-1 has only 34.9% grains larger than the #140 mesh, but this sample does have a low crush percentage as well.

The sieve data were plotted with the stratigraphic columns. The full sieve dataset is available in Appendix B.

**4. Correlation**

Correlation among cores and surface sections relies on gross lithology and physical position; elemental make-up of the lithologies by XRF scans were done to provide additional data. The contact between the upper and lower Tensleep Sandstone on the Bear Canyon surface stratigraphic section was extended through the study area.

**4.1. X-ray Fluorescence (XRF)**

The XRF data highlights calcium and silicon as elements that show possible correlations between all the cores. Calcium levels are high in dolomite, limestone, and carbonate cemented sandstone. Silicon levels are high in sandstones and siltstones. Calcium and silicon should therefore be inversely related, assuming there is not a significant amount of calcareous cement present in the sandstone. Because the top of the lower Tensleep Sandstone is a thick calcareous unit, the contact should show up on both the calcium and silicon graphs.
Much of the core appeared homogenous during visual inspection. The portable XRF allowed a quantitative elemental assessment of the rock that wouldn’t have been possible without a significant amount of time spend manually analyzing thin sections and hand samples.

A spike is expected in calcium levels whenever there is a limestone or dolomite layer. If there is a large amount of calcareous cement in a siliceous rock, the calcium levels should spike as well, but not as high as a calcareous rock will.

Silicon shows high levels in rocks made of quartz, and a low in limestones and dolomites. Because the top of the basal unit of the Tensleep Sandstone is a calcareous rock, silicon should be at a low point at that point. A large drop in silicon should correspond to the base of the upper member of the Tensleep Sandstone.

**4.1.1. Calcium and Silicon**

SS-5 has a slightly different profile than SS-1. Where SS-1 had almost no calcium in the upper Tensleep Sandstone member (shown in Figure 11), SS-5 has zones of relatively high calcareousness throughout both the upper and lower members (Figure 10). There is one 10’ zone with almost no calcium between 73’ and 83’, which indicates this is the only sandstone in the SS-5 location without calcareous cementation. The lower Tensleep Sandstone does still show higher calcium levels than the upper Tensleep Sandstone, so the marine influence is likely still occurred.

The SS-1 dataset indicates the Tensleep Sandstone has the least amount of calcium of all the cores, especially in the upper Tensleep member. The predominant trend of the data for SS-1 is high silicon levels, and low to zero percent calcium throughout the majority of the core. There is a 20’ layer of rock that has mixed calcium
and silicon percentages, meaning there is likely calcareous cementation present. At a few depths, the calcium and silicon values are reversed, indicating a calcite or dolomite section.

In the lower Tensleep Sandstone, the SS-1 data suggest that there is much more calcareousness cement in this lower section. This coincides with the idea of the lower Tensleep Sandstone having a heavy marine influence.

SS-11 (Figure 12) has a slightly different elemental profile than the other cores. Initial observation might indicate that a marine influence occurred in the upper Tensleep Sandstone and not the lower because of the high calcium percentages in the upper, and the high percentage of silicon present throughout most of the lower Tensleep Sandstone member. The amount of silicon and calcium occurring in the upper Tensleep Sandstone member indicate the rock present is probably sandstone with calcareous cement. These calcareous sandstones could be marine influenced sandstones capping eolian sand deposits.
Figure 10 - Calcium and Silicon from SS-5, showing a loose inverse relationship
Figure 11 - Calcium and Silicon from SS-1, showing a loose inverse relationship
Figure 12 - Calcium and Silicon from SS-11, showing a loose inverse relationship
4.1.2. Ratio Relationships

Plotting the ratio of Magnesium versus Calcium and Calcium versus Silicon can sometimes provide useful data when investigating rock types present. These ratio plots were created for each core.

4.1.2.1. Magnesium versus Calcium

In the depositional setting of the Tensleep Sandstone, calcium is predominantly present in limestone and magnesium is predominantly present within dolomite. The portable XRF machine used for elemental analysis can show inaccurate levels of elements when used on elements that are lighter atomically. One example of this is magnesium. To correct for this possibility, two known dolomites were analyzed along with the cores to show where pure dolomite would occur on a plot of magnesium versus calcium. These control points are plotted with each cores data. If the data from the cores plot near the known dolomites, it would be clear the rock is dolomitic. If the data from the cores plot with the same trend as the control dolomite, dolomite is present in the rock. If the percentages are low, the dolomite is likely in the cementation between the sand grains.

4.1.2.1.1. SS-5

The majority of core SS-5’s data shows up on the same trend of the control dolomites, suggesting a lot of dolomite is present in the core. The weight percentages of the data points are lower than the known dolomites though, so the dolomite is likely present between the sand grains in the rock. Four data points from core SS-5 are within one percent of the magnesium content of the known dolomites, which suggests some rock of the SS-5 core is dolomite.
Some data points have zero magnesium, and so plot on the x-axis. The points with no magnesium do have some calcium content, but don’t have a high percentage of calcium. Calcite cement sparsely present in sandstone could create this profile (Figure 13).

Figure 13 - Mg vs. Ca from SS-5 with control dolomites shown by red points
4.1.2.1.2. SS-1

Core SS-1 has a larger spread than the other two cores. More points lie at zero magnesium and zero calcium, and more points lie at or near the control dolomites than either SS-5 or SS-11. There are six points that clearly show the same percentages as dolomite, falling very near the control dolomite points meaning there is more dolomite in this core than the others. Many other points from this dataset also show up with no magnesium and small amounts of calcite, indicating calcite cement is present at those points (Figure 14).
Figure 14 - Ca vs. Mg from SS-1 with control dolomites shown by red points.
4.1.2.1.3. SS-11

A large portion of core SS-11’s data points have very little magnesium as well as only small amounts of calcium. The low calcium content with a zero magnesium content likely means small amounts of calcite cementation are present, and another type of cement is more dominant. At least three points, and as many as seven points, show the same content of magnesium and calcium as the control dolomites (Figure 15).
Figure 15 - Ca vs. Mg from SS-11 with control dolomites shown by red points
4.1.2.2. Calcium versus Silicon

A plot of calcium versus silicon could potentially show the relationship of carbonates to silicates within each core. The Tensleep Sandstone is presumably made of silicates, but carbonates present in the cement will show up on this graph, as will all calcareous members. All the graphs show a strong inverse linear relationship.

4.1.2.2.1. SS-5

The majority of the data points for SS-5 have less than 5% calcium and over 30% silicon. The data with low calcium content show more variability in silica content than the data with high calcium content. This is especially apparent for data points with less than 15% calcium. Points greater than 15% calcium appear to have less variability in silica content, and the data is much more linear. The highest percentage of calcium in this dataset, at 21% calcium, is the lowest high point of all the datasets. This suggests there is the least amount of calcareous deposition and cementation in this core (Figure 16).
Figure 16 - Ca vs. Si for SS-5 showing an inverse relationship
4.1.2.2.2. **SS-1**

Much of SS-1’s data have less than 10% calcium. With a few exceptions, 10% calcium is a divide, with data greater than 10% calcium showing less variability in silica content than the data points with less than 10% calcium. This graph is the least linear of all the cores below 10% calcium, but the data is much more linear above that. This dataset has the highest calcium content of all the cores, with the maximum reaching nearly 27.5% calcium. Two data points have close to zero percent silica, showing some potential limestones or dolomites. This core is the most calcium rich of all the cores (Figure 17).
Figure 17 – Ca vs. Si for SS-1 showing an inverse relationship
4.1.2.2.3. SS-11

SS-11 has the highest percentage of data at or extremely close to zero percent calcium. Much of the data is scattered throughout the rest of the graph, and not much data is present above 10% calcium. Ten data points are below 10% silicon on this graph, and three of those are above 20% calcium (Figure 18).
Figure 18 – Ca vs. Si for SS-11 showing an inverse relationship
4.2. Correlation of Stratigraphic Sections

A cross section through the project area was created in order to propose correlations between the surface and subsurface sections. The base map for the cross section is shown in Figure 4. The cross section is a well to well section, and includes the core locations and the relevant surface measured sections. The complete cross section is shown below in Figure 19.
Figure 19 - Stratigraphic cross section through area of interest with proposed correlation of base of upper Tensleep Sandstone
5. **Microscopic Analysis**

The thin sections show that there is great variability in the grain size, grain shape, porosity and cementation present in each of these cores. There are multiple grain sizes and grain shapes in each thin section. Both calcite and dolomite are absent, as red staining is infrequently seen in the thin sections. Every thin section has at least a small amount of calcite and/or dolomite present, but it appears to be secondary to siliceous or evaporitic cements. Photographs have been taken of all thin sections and are included in Appendix C.

5.1. **Petrographic**

5.1.1. **Porosity**

Porosity is easy to pick out in the thin sections due to the blue epoxy used to hold the grains together on the thin section slide. All thin sections have abundant porosity, but porosity was not quantified; thin sections with smaller grain sizes appear to have less porosity. Sample 9 of SS-11 (Figure 20) is a good example of a relative high porosity zone in the Tensleep Sandstone.
Figure 20 - Sample 9 from core SS-11 of subrounded-rounded quartz grains (yellow) and open pore space (filled by blue-dyed epoxy)
5.1.2. Grain Shape

The Tensleep Sandstone has a range of grain shapes throughout the thin sections. Most common is subangular to subrounded with some angular grains and some rounded grains. Sample 5 from SS-11 (Figure 21) is an example of angular grains in the Tensleep Sandstone. Sample 3 from SS-11 (Figure 22) shows the rounded grains present in the Tensleep Sandstone.
Figure 22 - Sample 3 from core SS-11 of subrounded-rounded quartz grains (yellow) and open pore space (filled by blue-dyed epoxy) with some calcareous cementation
5.1.3. Grain Size

In the thin sections made from the Tensleep Sandstone, grains more angular appear to be smaller in size than the more rounded grains. Sample 1 from SS-5 (Figure 23) shows large grains on the bottom of the picture, and much smaller grains at the bottom.
Figure 23 - Sample 1 from core SS-5 of subrounded-rounded quartz grains (yellow) of varying size.
5.1.4. Cementation

The thin sections do not show much calcareous cementation. There are some faint red stains on many of the thin sections, but the majority of the cement is not stained. Sample 3 on SS-11 (Figure 22) shows red stained cementation in pockets throughout the thin section, but the areas of calcareousness are isolated by siliceous and possibly evaporitic cementation.

Sample 4 of SS-5 (Figure 24) shows cementation that isn’t calcareous. There is no red staining present anywhere in the photo.
Figure 24 - Sample 4 from SS-5 of non-calcareous cementation
5.2. Binocular

The average sphericity and roundness for all samples was 0.7, although there was some variation. Sphericity ranged from 0.5 to 0.8. Roundness ranged from 0.6 to 0.8. Sample 9 (137’) from SS-1 had the lowest sphericity of 0.5, and Sample 8 (97’) and Sample 9 (105’) from SS-5 had the highest sphericity of 0.8 (Figure 25). SS-1 had both the lowest and highest roundness values; Sample 9 (137’) and Sample 10 (147’) had roundness values of 0.6. Sample 6 (61’) of SS-1 had the highest roundness value of 0.8 (Figure 26).
Figure 25 - Sphericity of samples from SS-1 and SS-5

Figure 26 - Roundness of samples from SS-1 and SS-5
Modal Mineralogy

The results from the Mineral Liberation Analysis are shown in Figure 27. The MLA results show no calcite in either test conducted and only a small percentage of dolomite. Feldspar and quartz make up the vast majority of the samples tested. This agrees with the microscopic analysis of the thin sections. Samples used for MLA are extremely small so the absence of calcite could correspond to one of the many areas seen in the thin sections that are not cemented by calcareous precipitates. The dolomite present in the MLA test likely resulted from the dolomite concretions evident in the thin sections.
Figure 27 - Modal mineralogy of Sample 2 (43’) of SS-5 from Mineral Liberation Analysis (MLA)
Discussion

The base of the upper Tensleep Sandstone was picked by Lopez et al. (2007) in his surface measured section of the Bear Canyon. The rock descriptions listed in his paper were the basis for this project’s interpretation of where that contact is in the cores investigated. The contact was chosen using lithology, grain size, and cementation descriptions.

The surface sections characterizes the upper Tensleep Sandstone as eolian sand and the lower as a marine deposit. In the Bear Canyon surface section, the upper Tensleep Sandstone doesn’t show any calcareous cement in sandstone. Based on this, correlating the contact was tried using the presence of calcareousness. Unfortunately, all cores east of Bear Canyon had calcareous cement in both the upper and lower members of the Tensleep Sandstone so basing the correlation on cementation type was fruitless.

Lopez et al. (2007), showed the contact between the upper and lower Tensleep Sandstone is picked at the top of the highest limestone or dolomite zone thicker than 3 feet present in the Tensleep Sandstone. The surface sections also showed that high angle trough crossbeds occurred in the upper Tensleep Sandstone member, but are not present in the lower member. This criterion was used to correlate the base of the upper Tensleep Sandstone in Figure 19. The depth of the contacts from each core is listed below in Table 1.
Compiling the stratigraphic sections with the XRF data and the Proppant Research Division’s data gives a general framework for determining whether the Tensleep Sandstone in the project area would be suitable for hydraulic fracture proppant. Grain size, crush testing, and samples all portray the lower Tensleep Sandstone member as coarser grained and stronger on average than the upper Tensleep. Although the lower Tensleep is more favorable than the upper member, the potentially useful zone is only between 10 and 50 feet thick (Figure 28). The other obstacle is the ability to disaggregate the Tensleep Sandstone in the project area. As the thin sections and MLA results show, not much of the cementation in any of these cores is calcite or dolomite. The most promising footage for calcareous cementation is from 40’ to 50’ of SS-11, but the thin sections still only spotty calcareous cement and over half of the 10’ zone is limestone.

The calcium and magnesium amounts measured by the XRF were useful in highlighting limestones and dolomites in the cores. The XRF data also validated the core lithology descriptions. Actual mineralogy of the cement in a sandstone can be hard to identify in hand sample, even with dilute HCl and a hand lens.
Figure 28 - Final correlation of project area with potentially useful zones identified
Conclusion

The Tensleep Sandstone changes stratigraphically throughout its regional extent. In the study area, analyzing the drilled cores and gathering portable XRF data allowed rough characterization of the informal upper and lower units of the Tensleep Sandstone to take place based on the surface sections measured by Lopez et al. (2007). Compiling all the datasets on the Tensleep Sandstone in the area of interest gave insights into the differences between the upper Tensleep Sandstone and the lower Tensleep Sandstone members.

Creating a stratigraphic section for each core and surface sections to compare visually was a good starting point for understanding the stratigraphic signature of the Tensleep Sandstone in this area. Comparing the portable XRF data and the stratigraphic sections confirmed the contact between the upper and lower Tensleep Sandstone is at the top of a calcareous layer thicker than 3 feet.

Using the data from the Proppant Research Division, the Center for Advanced Mineral and Metallurgical Processing, and the stratigraphic sections drawn, a better sense of the suitability of the Tensleep Sandstone as proppant can be understood. The sieve data shows grain sizes in the useable spectrum for proppant material. The MLA and XRF data show areas of high silica content. The stratigraphic sections show the thickness of possible mineable zones along with their location stratigraphically and overburden above them. The thin sections and core descriptions show that cementation is mostly not calcareous, which could impede use of the Tensleep Sandstone as a potential fracture proppant.
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Appendix A – Core Logs
Appendix B – XRF Data
Appendix C – Proppant Research Division Data
Appendix D – Thin Section Photographs
Appendix E – Core Photographs