Silica Diagenesis and its Pore-Scale Influence on the Characteristics of the Upper and Lower Bakken Shales, Williston Basin, North Dakota and Montana

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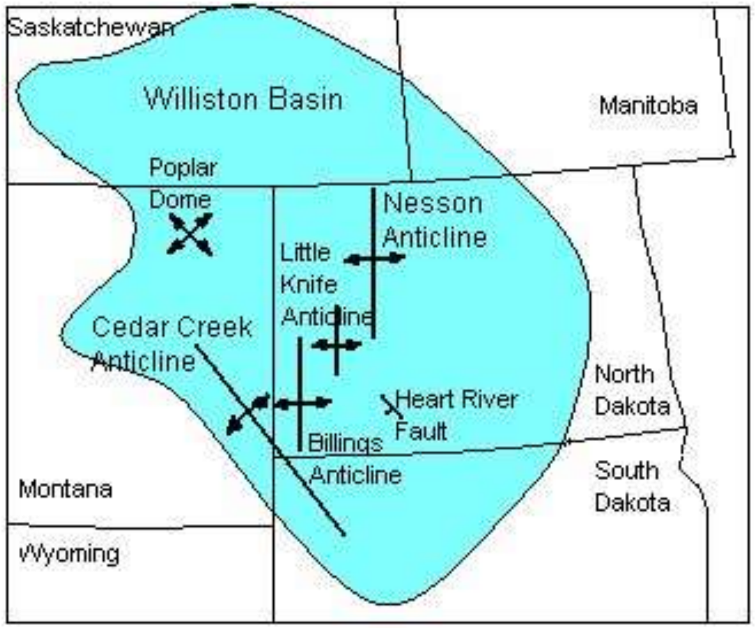
Outline

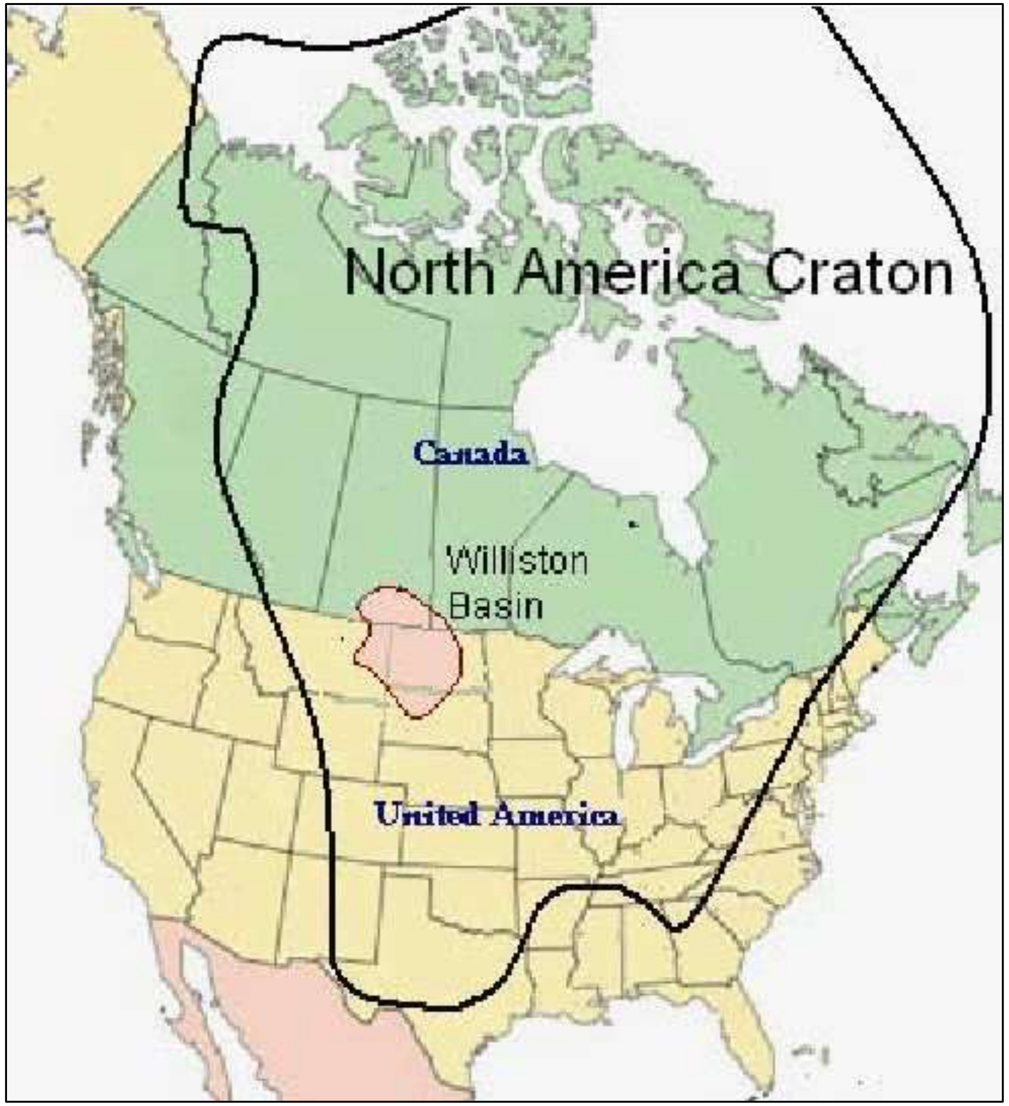
- Project Introduction
- XRF Data
- Microscopy
- XRD Data
- NO2 Physisorption Data
- Conclusions and Recommendations for Future Analysis

The Williston Basin

- Intracratonic Basin above Precambrian Trans-Hudson Orogenic Belt
- Variable subsidence from Cambrian to Mesozoic
- Laramide Orogeny-reactivated basement structures

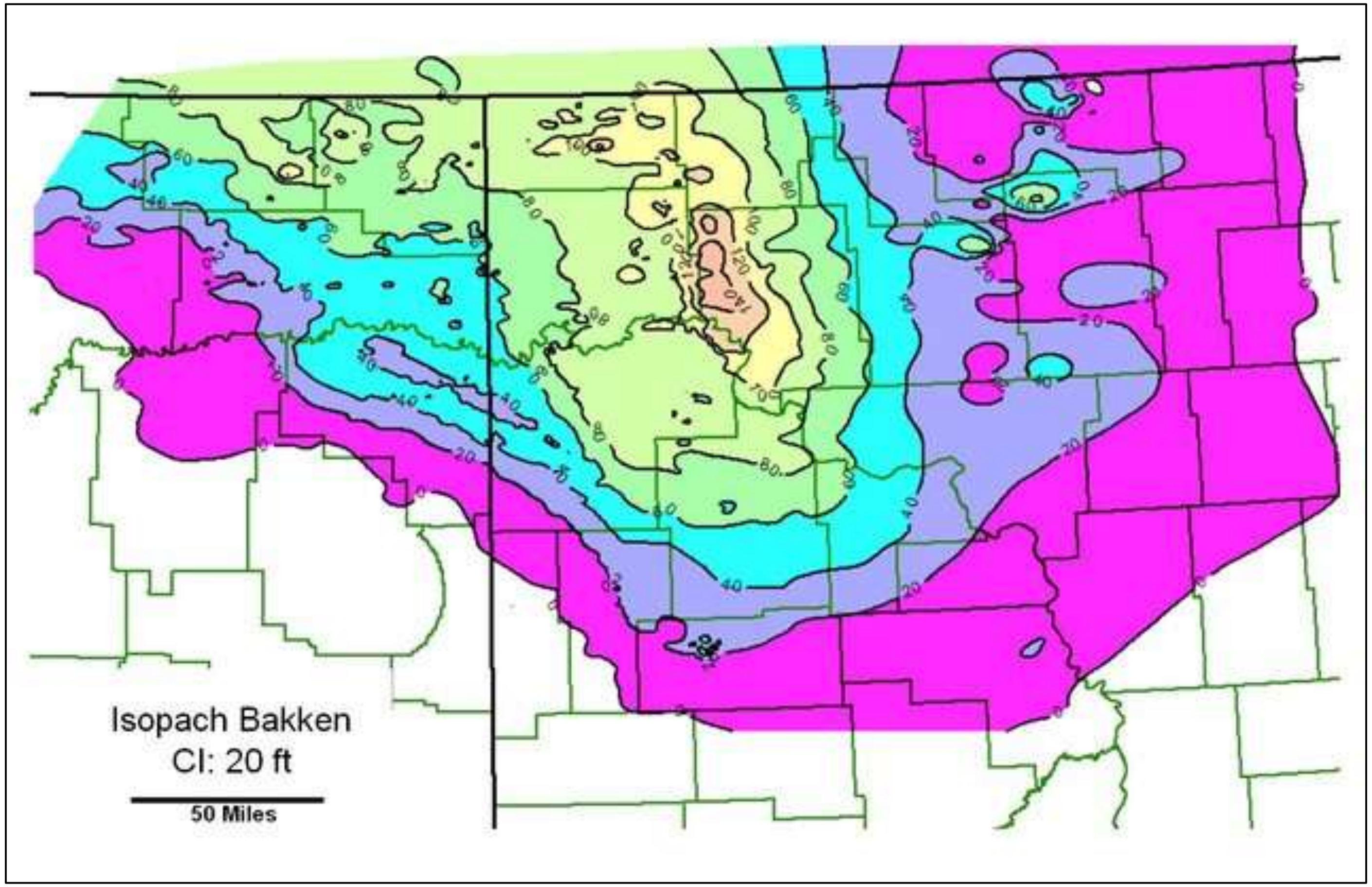


Zhou et al., 2008

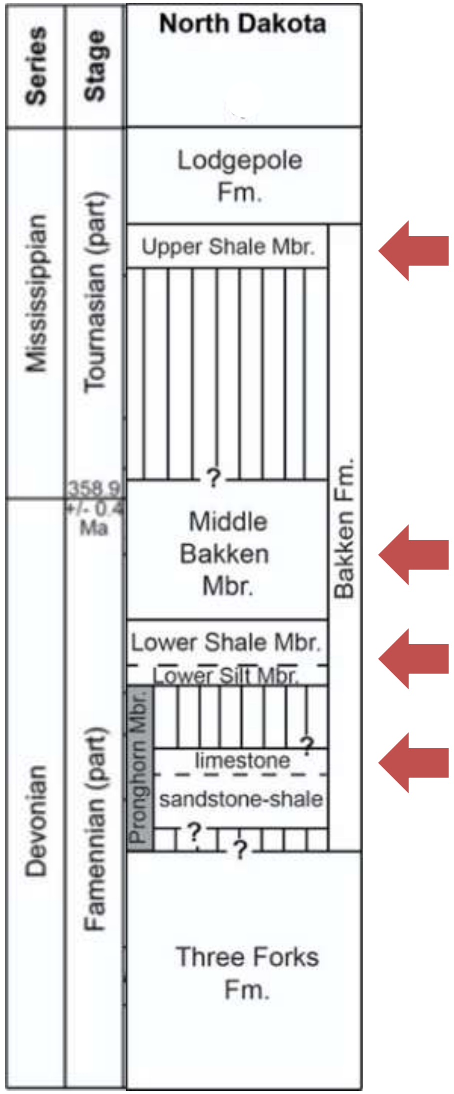


Zhou et al., 2008

The Bakken Formation



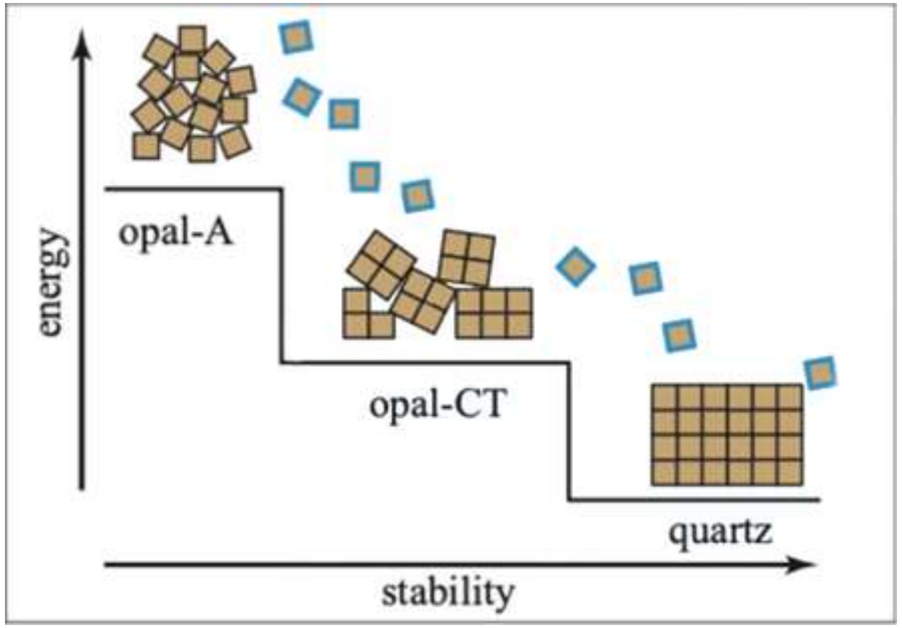
Isopach Map of the Bakken Formation. Thickness ranges from wedge-edge to over 140 feet. From Sonnenberg et al., 2011



Sandberg et al., 1988

Silica Diagenetic Sequence

Below is the basic sequence of silica transformation during diagenesis, but in reality it is very nuanced. We will look at some examples of each phase in some interesting SEM photos.



Modified from Dralus, 2013

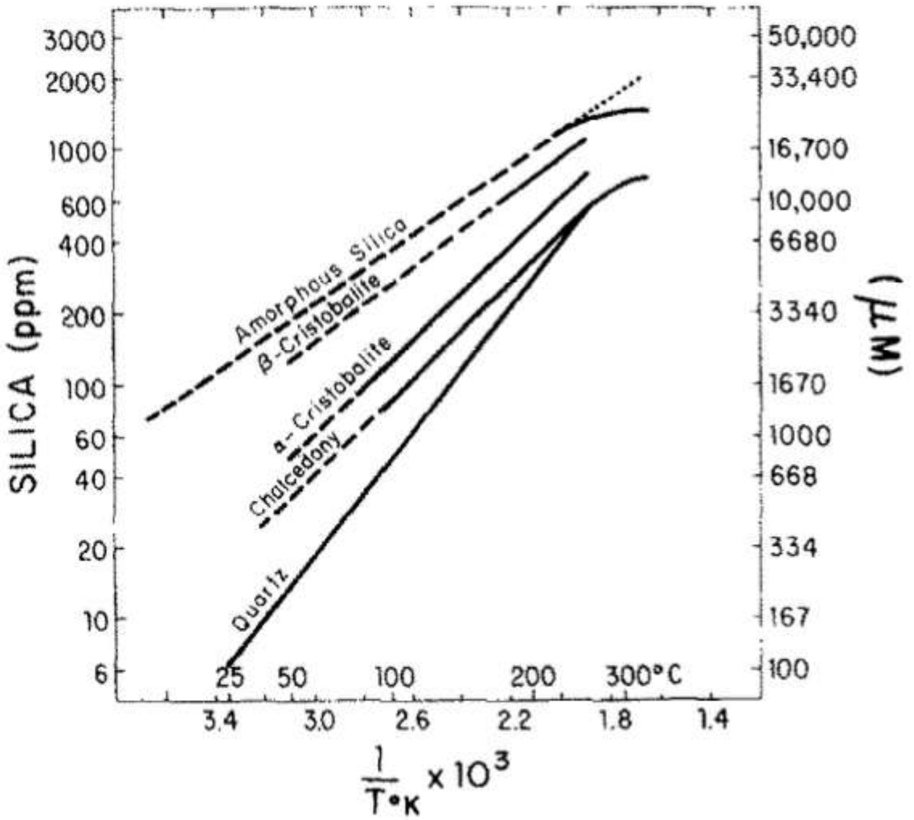
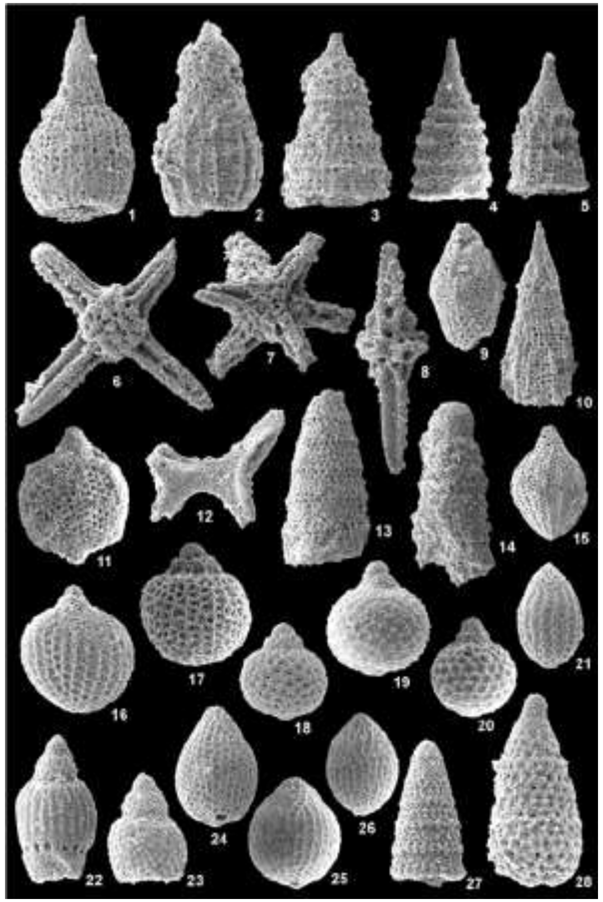


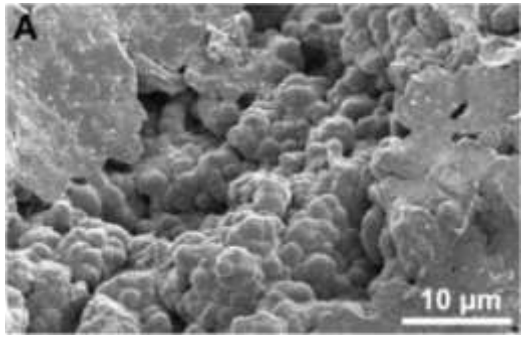
Fig. 1. Solubilities of the various silica phases along the two-phase curve, water plus vapor. Plotted as log concentration vs. reciprocal of absolute temperature, after FOURNIER (1973, Fig. 2).

From Kastner et al., 1977.

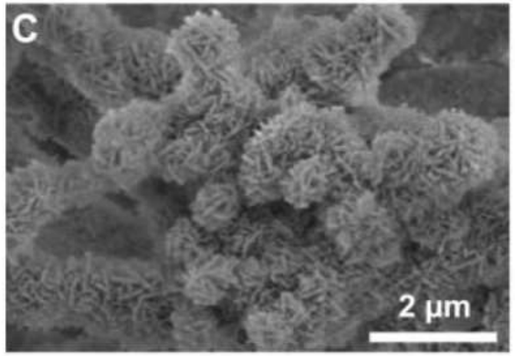
Silica Diagenetic Sequence



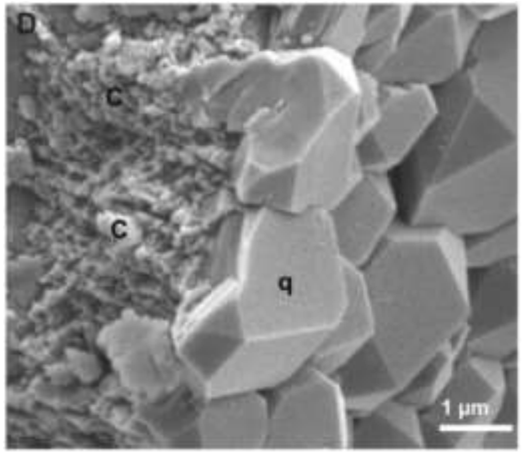
Robin et al., 2010.



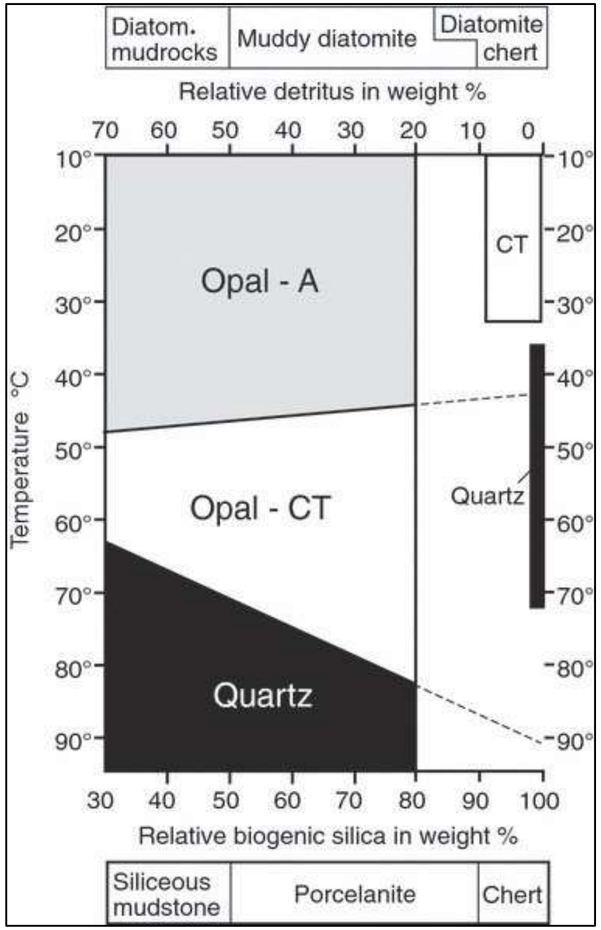
Lynn et al., 2007



Lynn et al., 2007

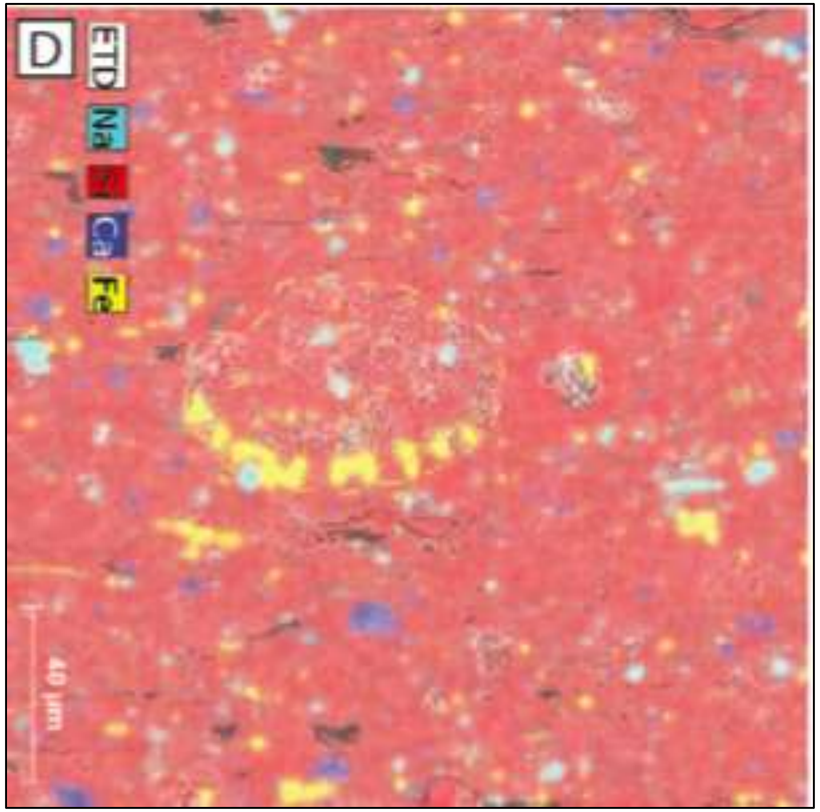


Lynn et al., 2007

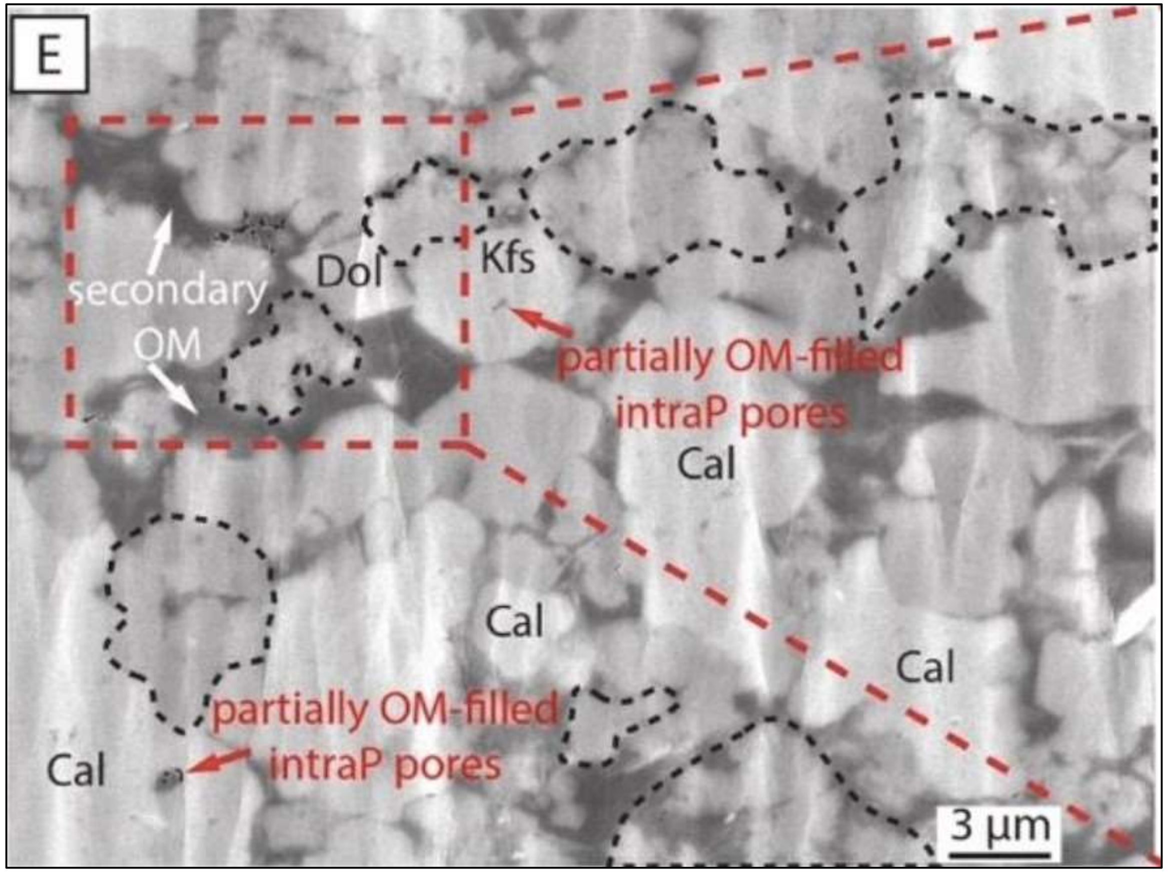


Behl, 2010

Motivation for Study



X-ray elemental map of a dissolved radiolarian test (dashed line) being replaced by pyrite in the Mowry shale *(Milliken and Olsen, 2017)*



SEM Photomicrograph of authigenic microquartz (dashed lines), K-feldspar, calcite, and organic matter *(Xu, 2019)*

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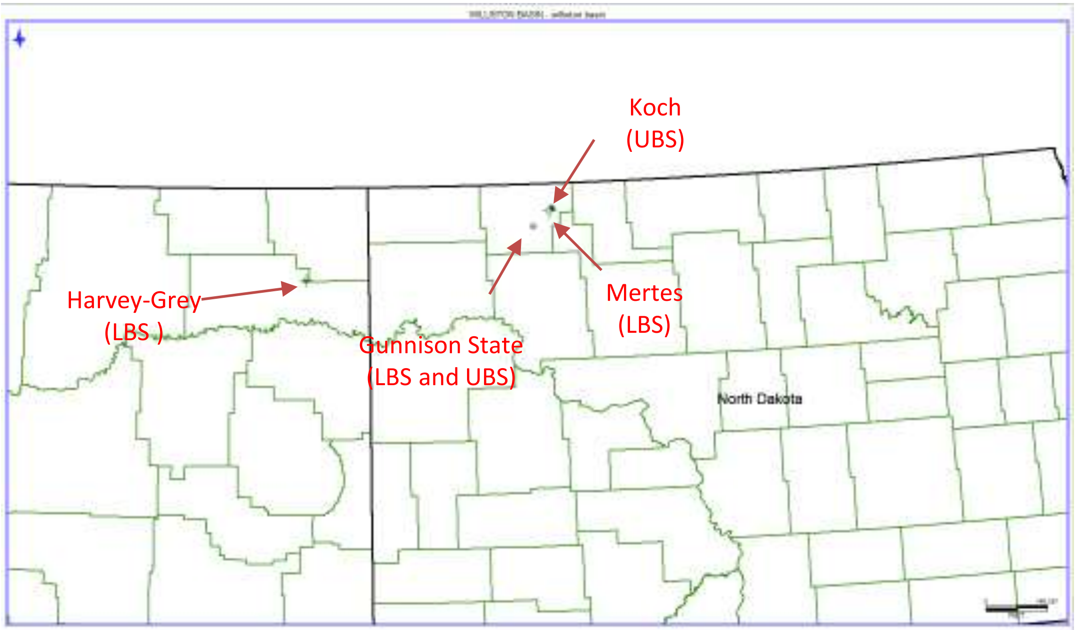
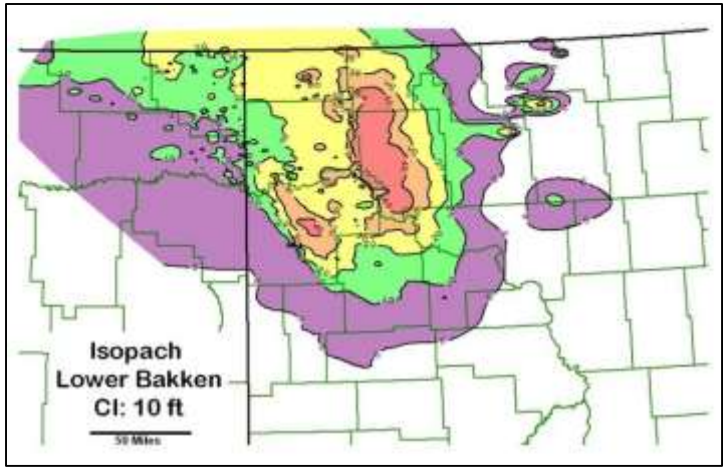
Core Overview: Locations



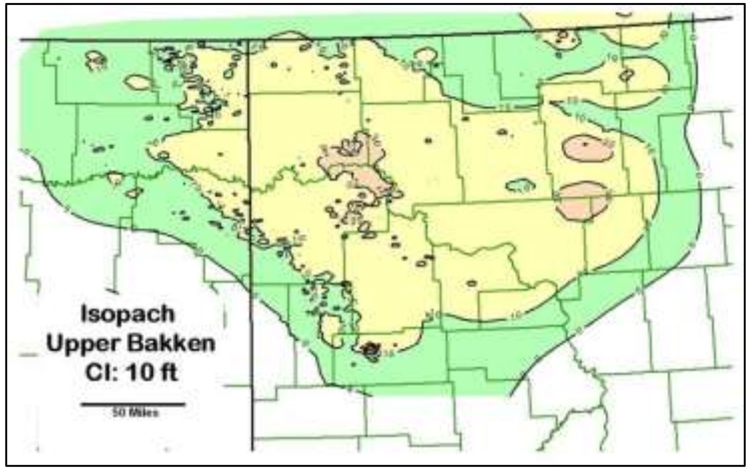
Gunnison State

Clarion Mertes

Koch



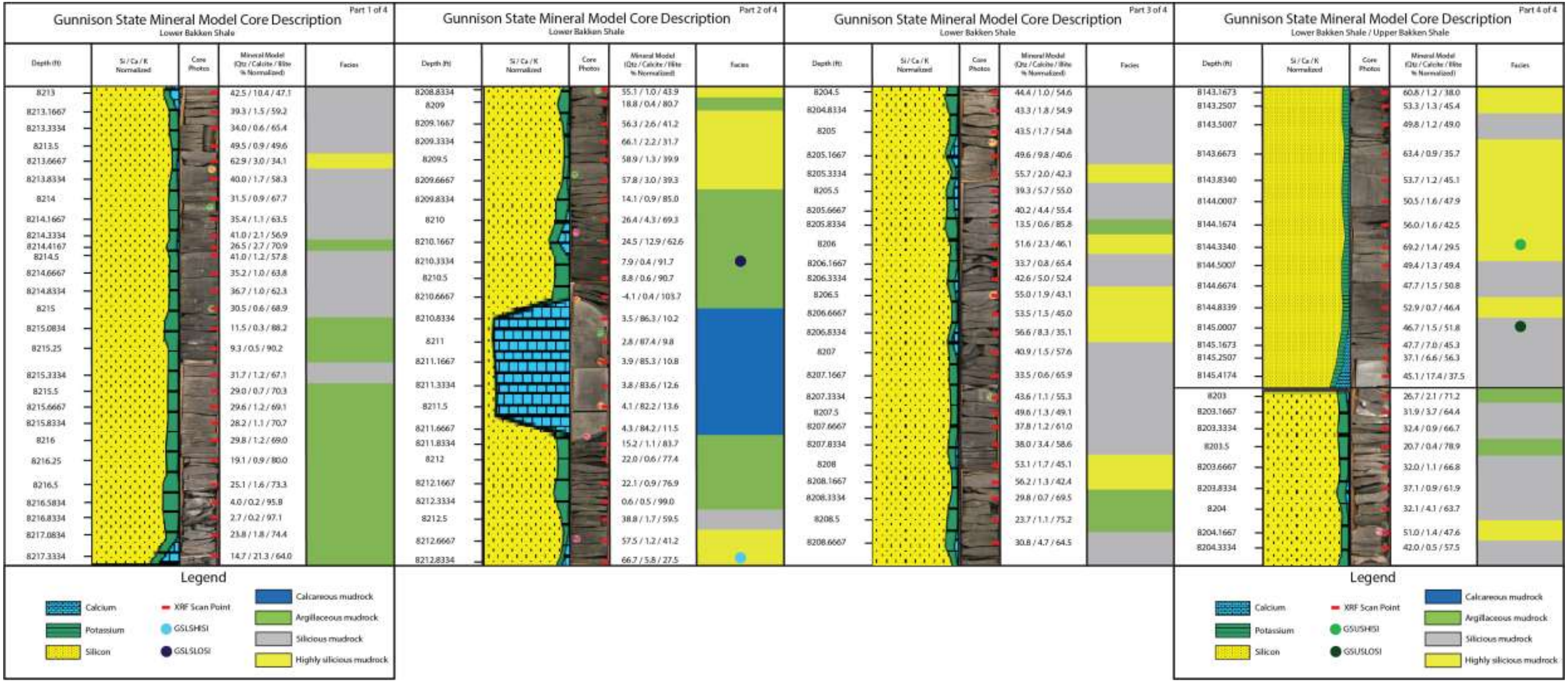
Sonnenberg et al., 2011



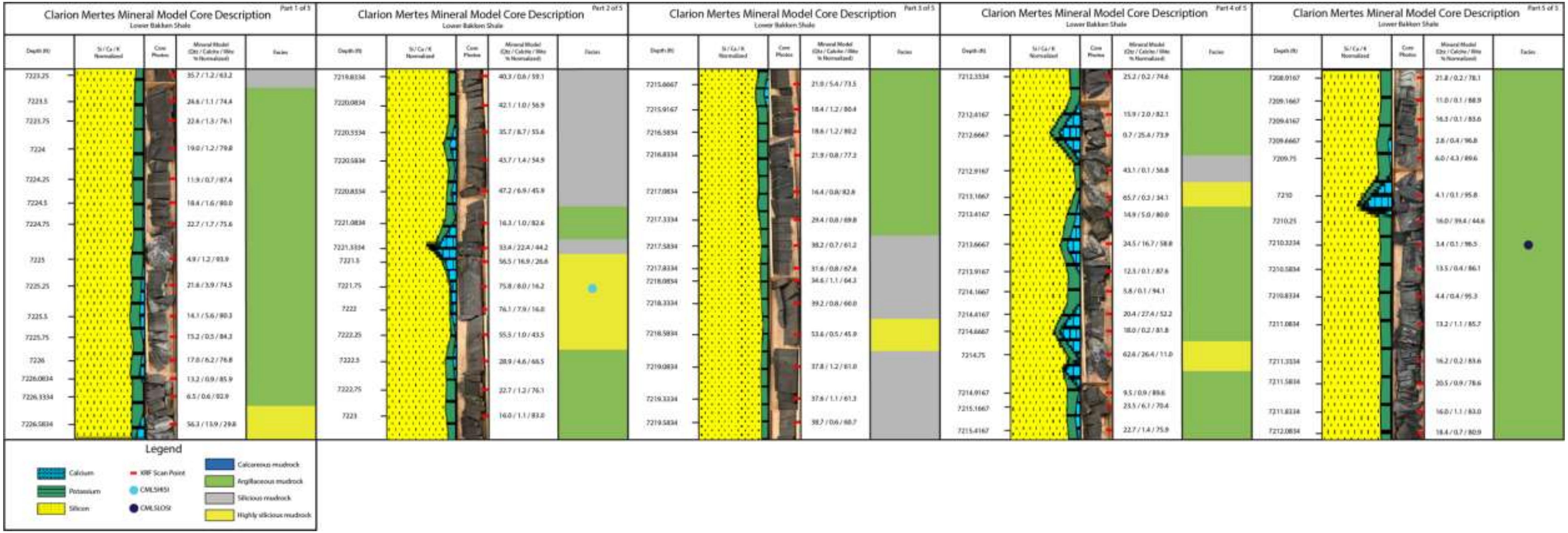
Sonnenberg et al., 2011

Harvey Grey

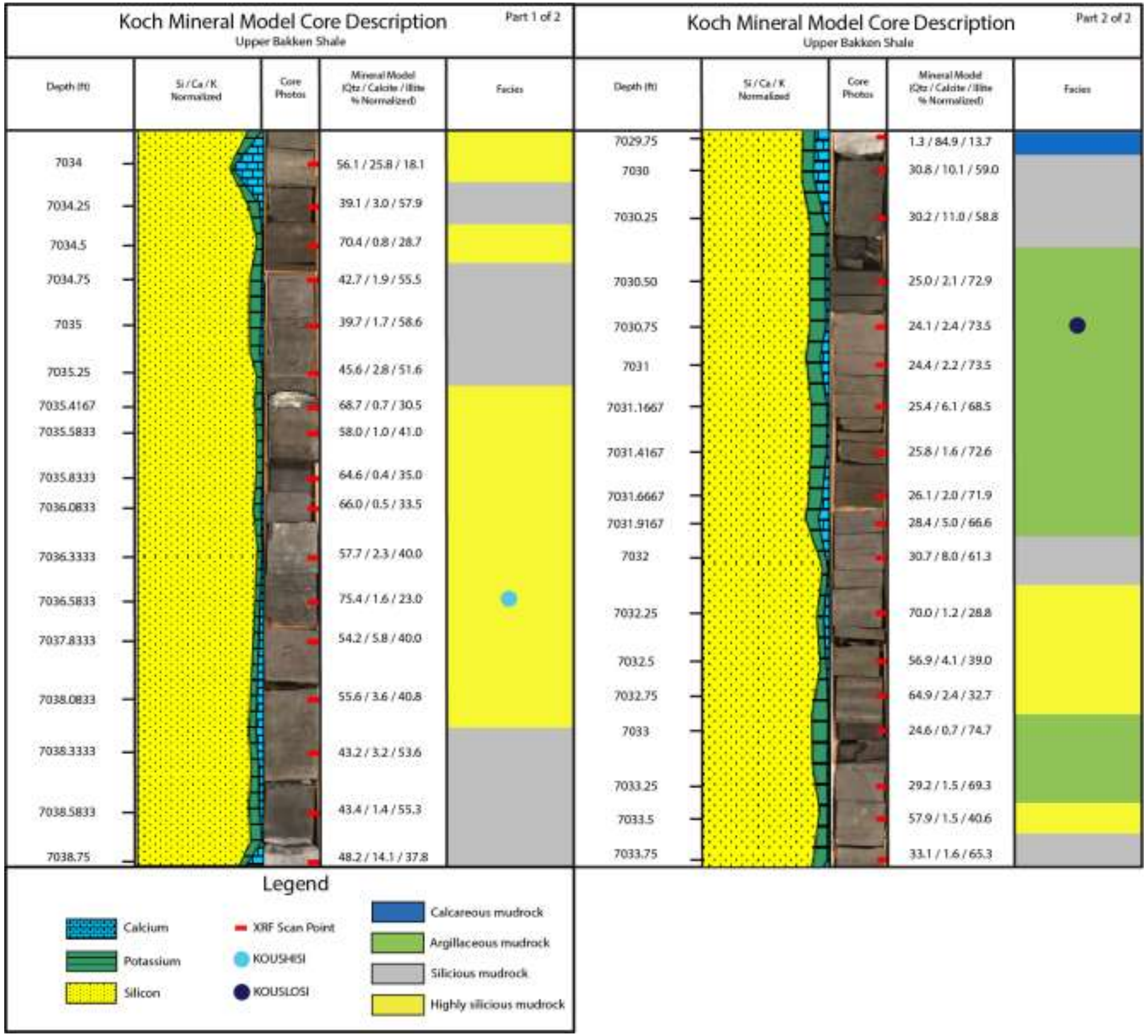
Core Description: Gunnison State



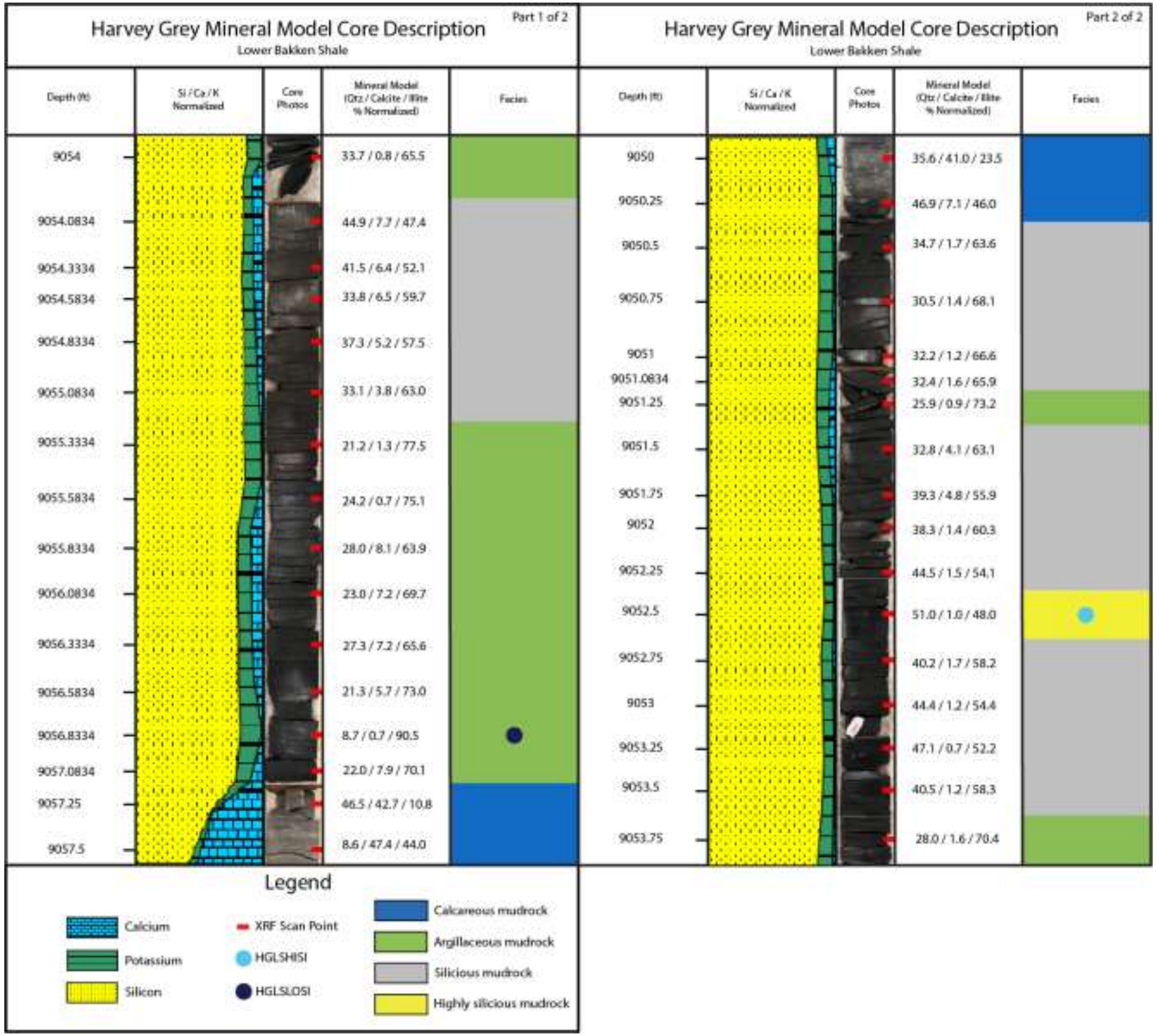
Core Description: Clarion Mertes



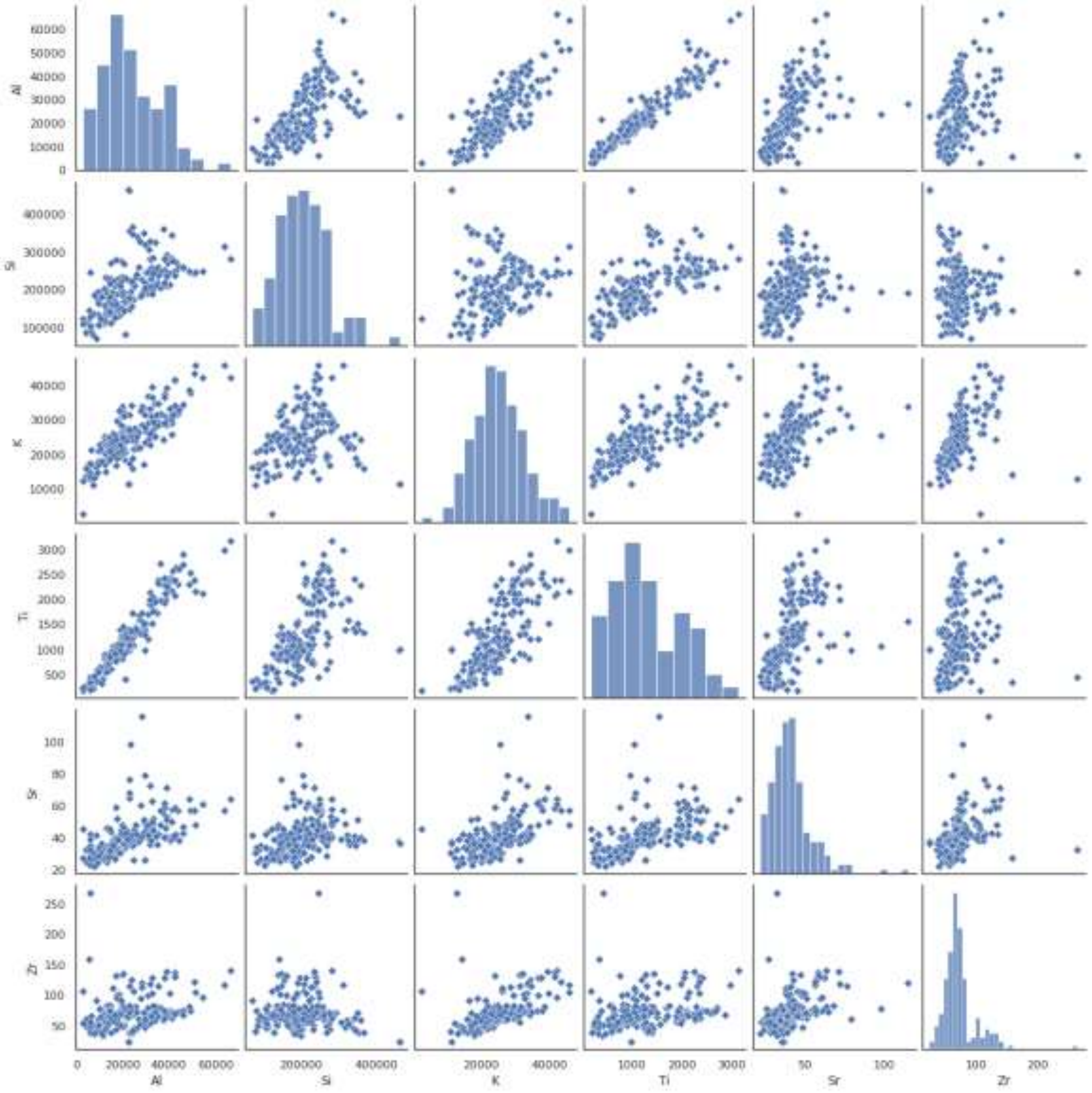
Core Description: Koch



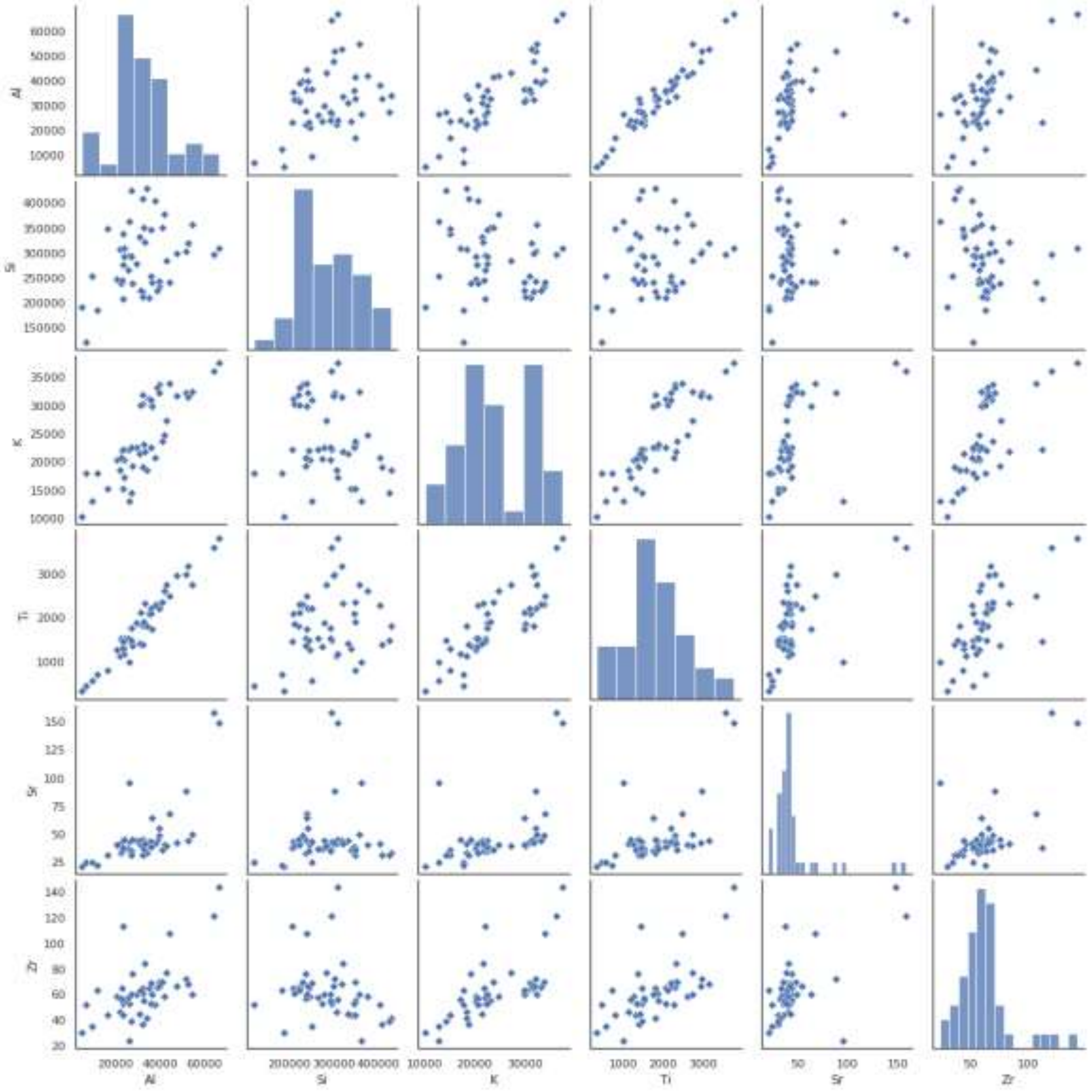
Core Description: Harvey Grey



Using Python on XRF Data: Visualizations

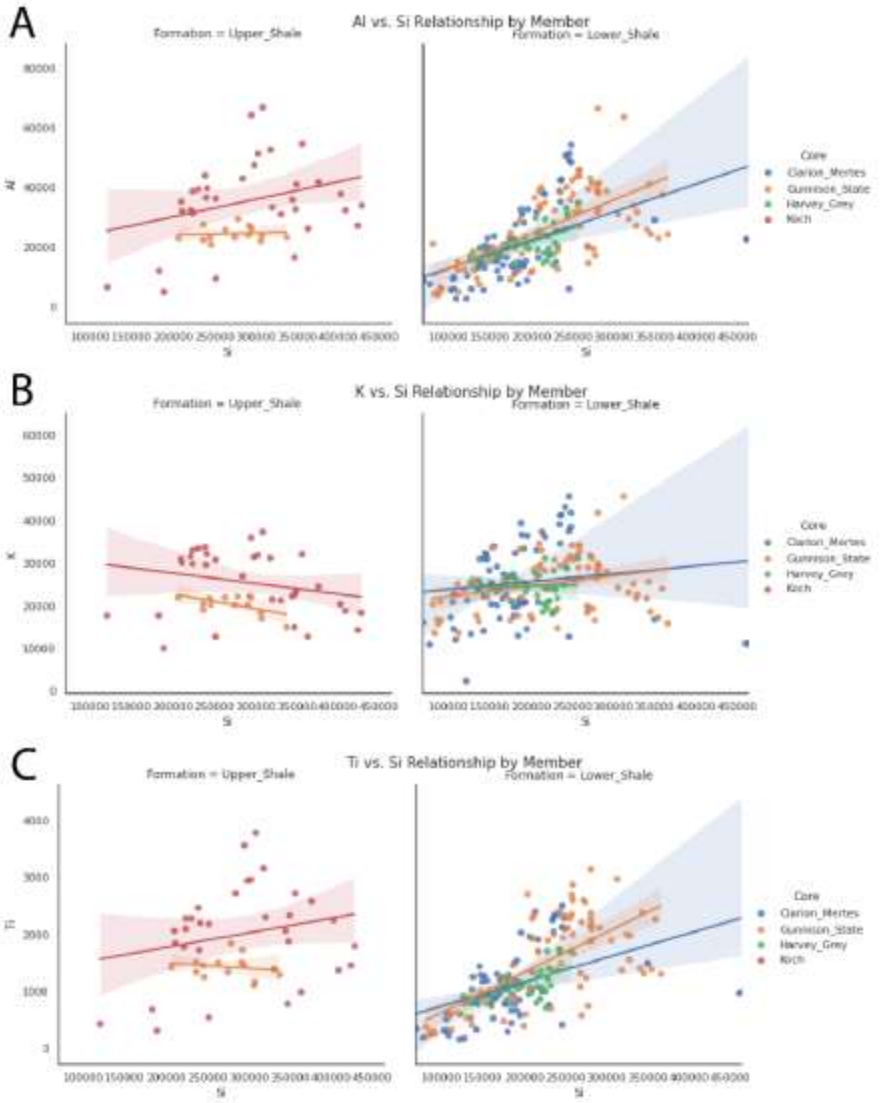


Lower Bakken Shale

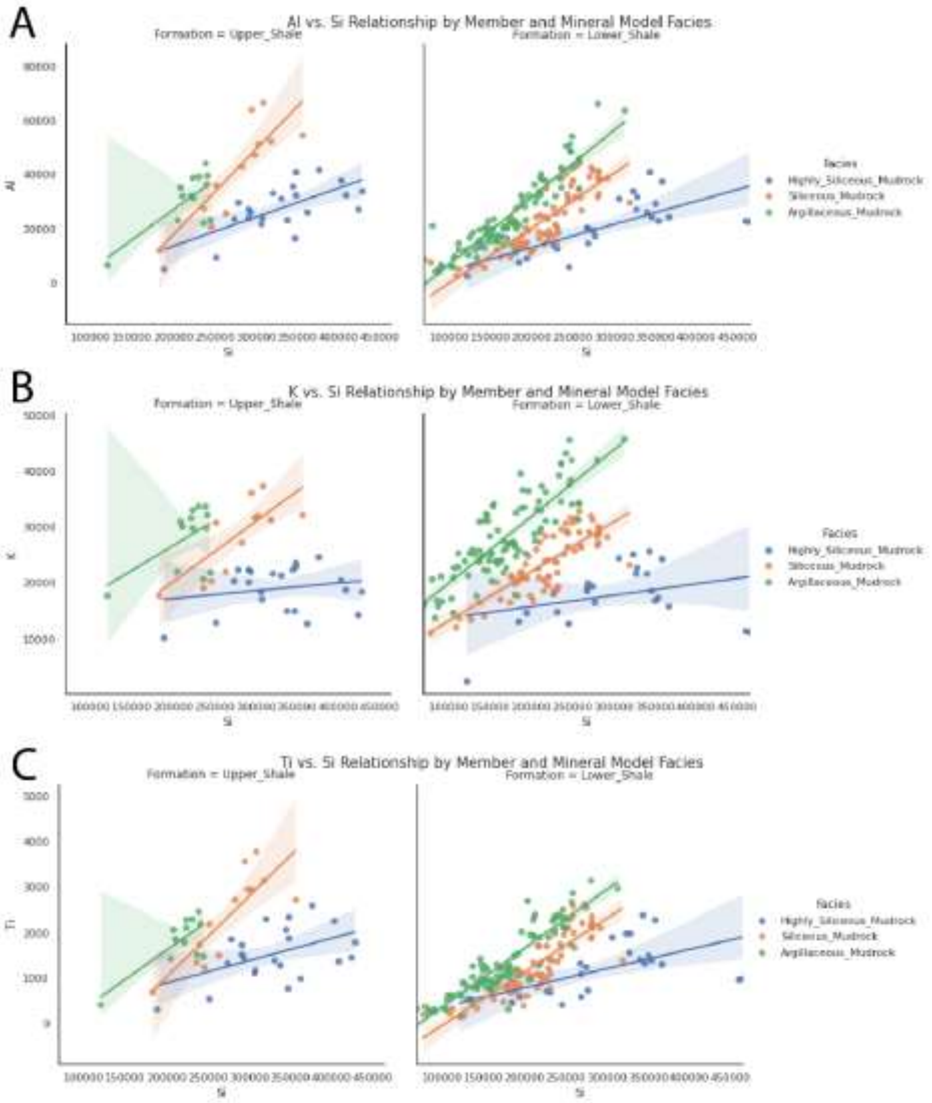


Upper Bakken Shale

Using Python on XRF Data: Visualizations

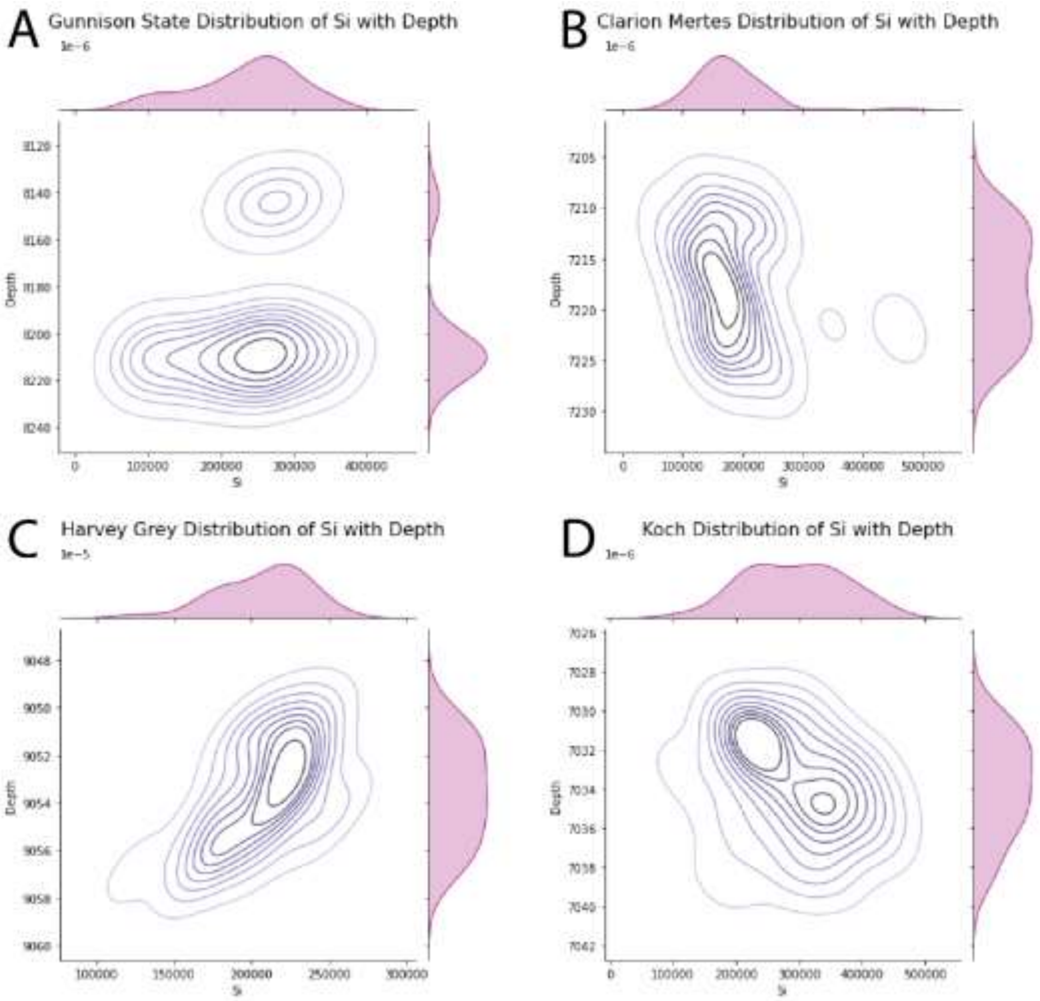


Comparison by Core

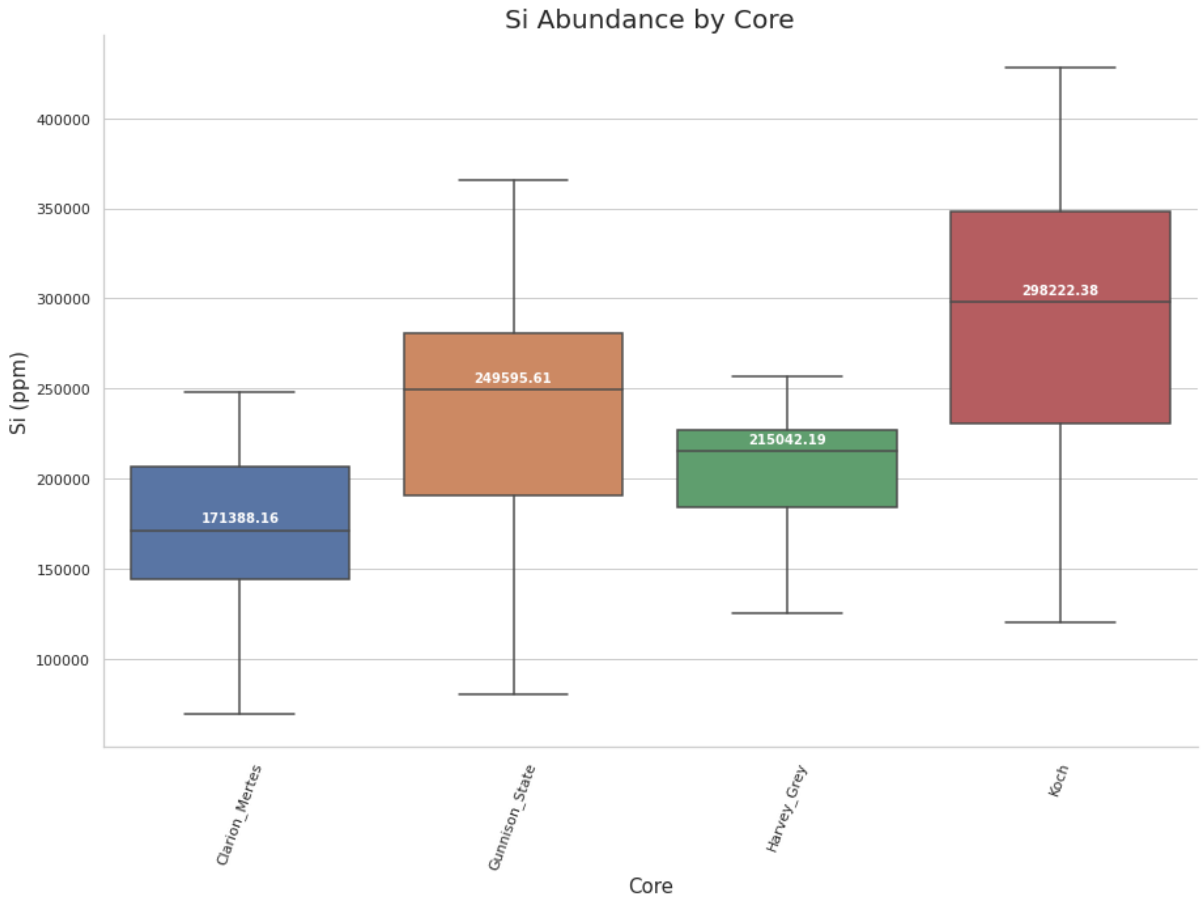


Comparison by Facies

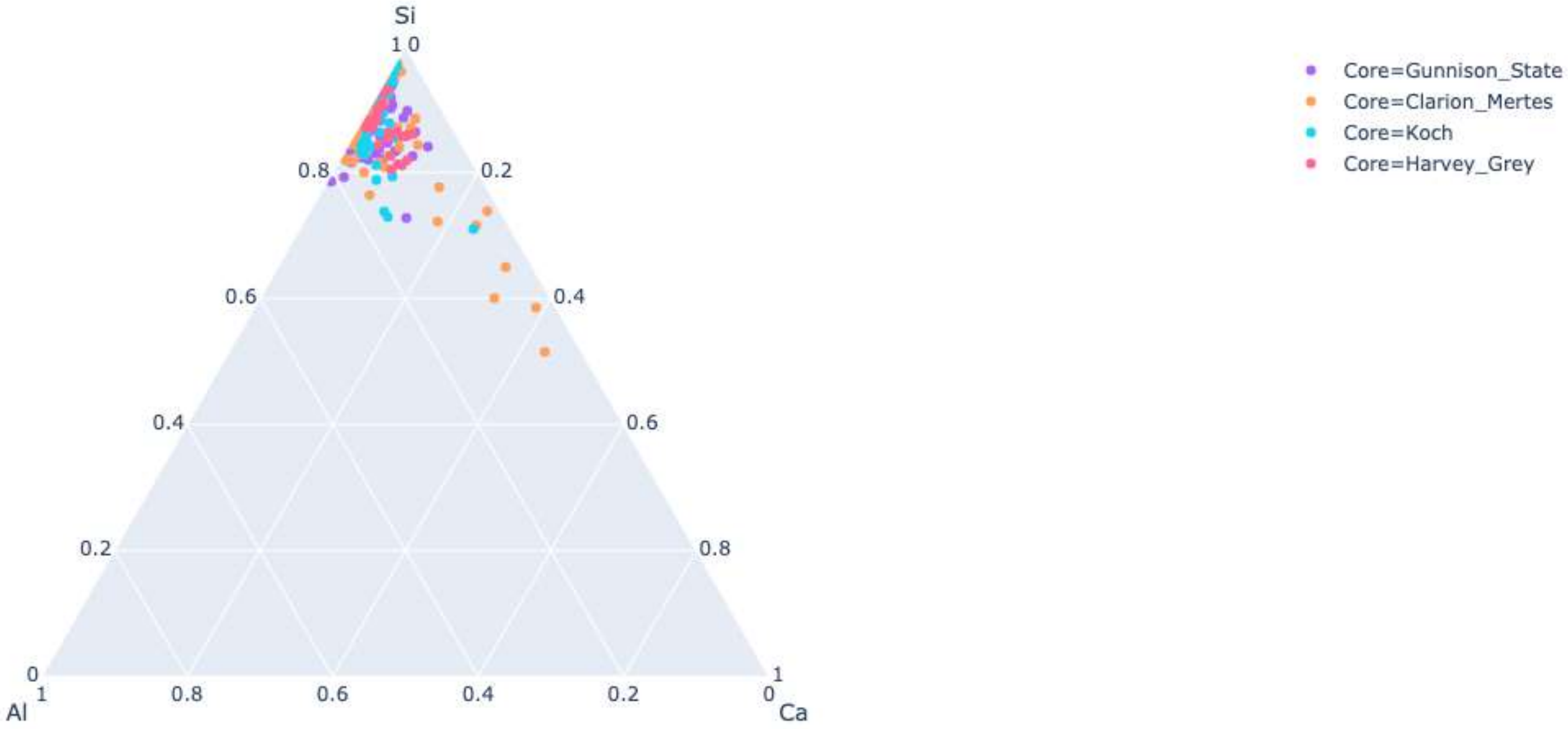
Using Python on XRF Data: Visualizations



Si Concentration Jointplots with KDEs



Using Python on XRF Data: Visualizations

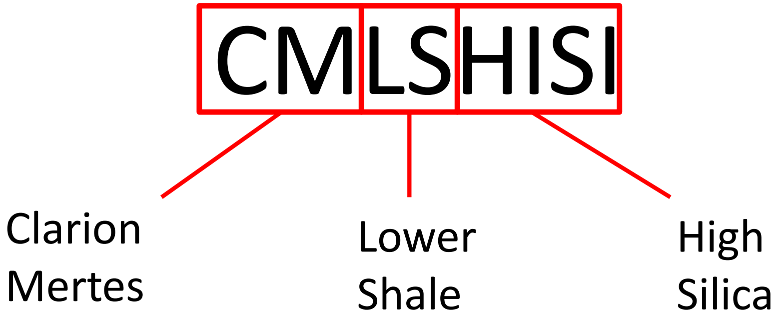


Using Python on XRF Data: Statistics

	10th Percentile (Si wt%)	50th Percentile (Si wt%)	90th Percentile (Si wt%)
Gunnison State	12.23	24.96	32.20
Clarion Mertes	12.13	17.14	24.49
Harvey Grey	17.52	21.5	24
Koch	20.92	29.82	39.77
Lower Shale	12.25	20.42	28.17
Upper Shale	21	29.12	36.81
Argillaceous Mudrock Facies	10.64	17.72	24.44
Siliceous Mudrock Facies	16.44	22.95	28.32
Highly Siliceous Mudrock Facies	22.89	32.52	40.58

Sampling Methodology

Sample Names	Sampled Core	Sample Depth (ft)	Relative Silica Concentration
CMLSHISI	Clarion Mertes	7221.75	High
CMLSLOSI	Clarion Mertes	7210.33	Low
HGLSHISI	Harvey Grey	9052.50	High
HGLSLOSI	Harvey Grey	9056.83	Low
GSLSHISI	Gunnison State	8212.83	High
GSLSLOSI	Gunnison State	8210.33	Low
GSUSHISI	Gunnison State	8144.33	High
GSUSLOSI	Gunnison State	8145.00	Low
KOUSHISI	Koch	7036.58	High
KOUSLOSI	Koch	7030.75	Low



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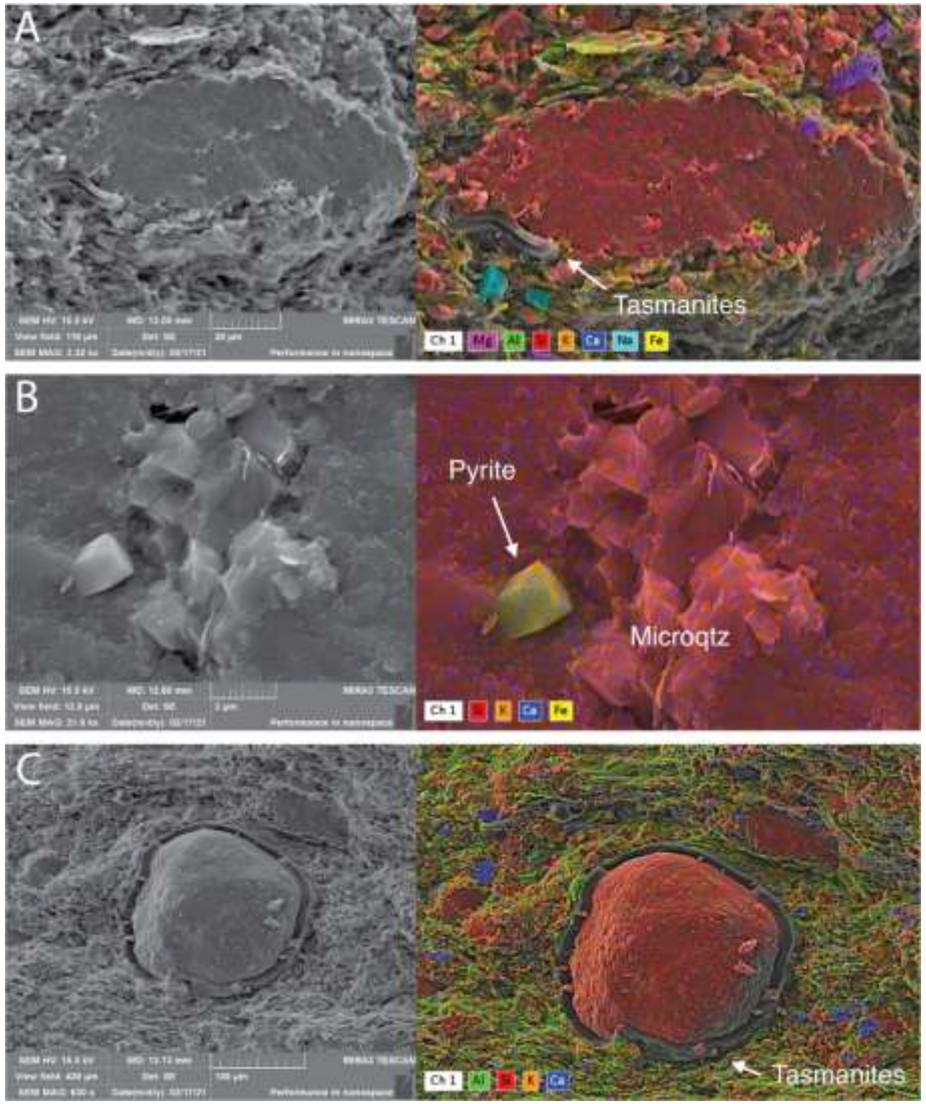
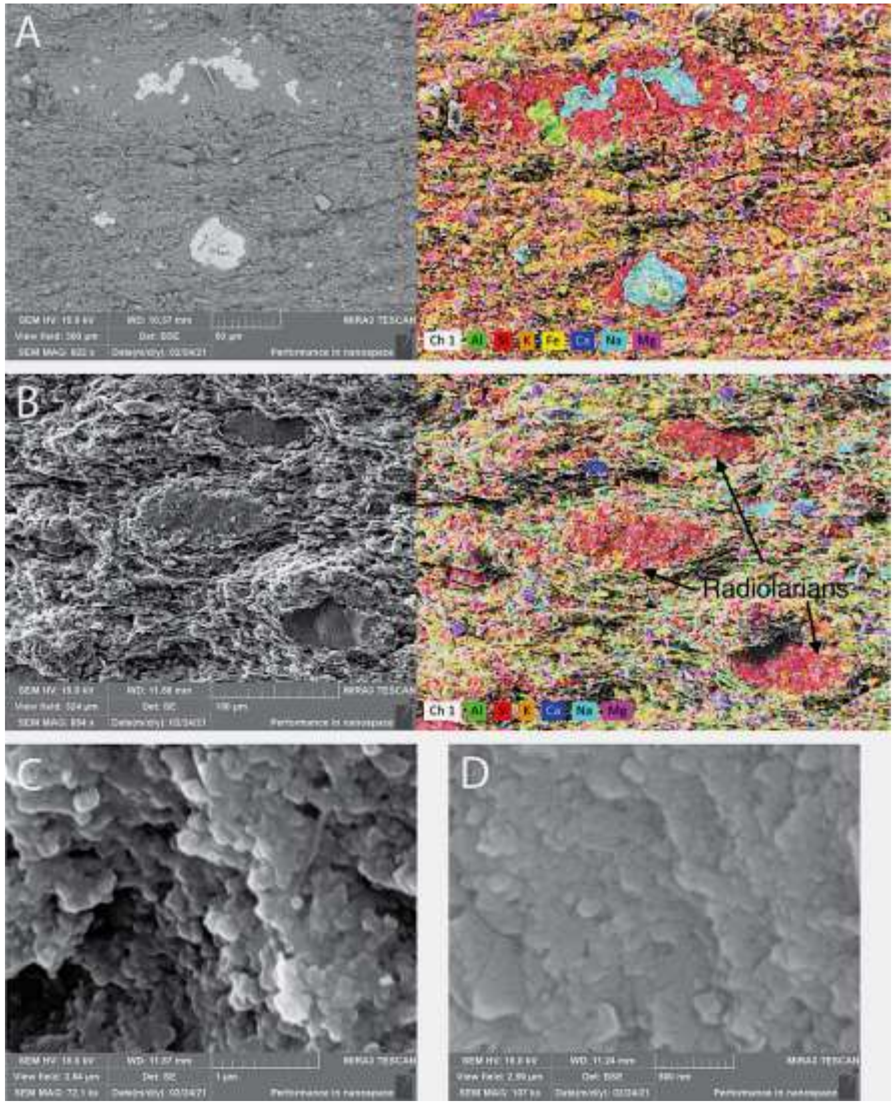
FESEM Analysis: High-Silica

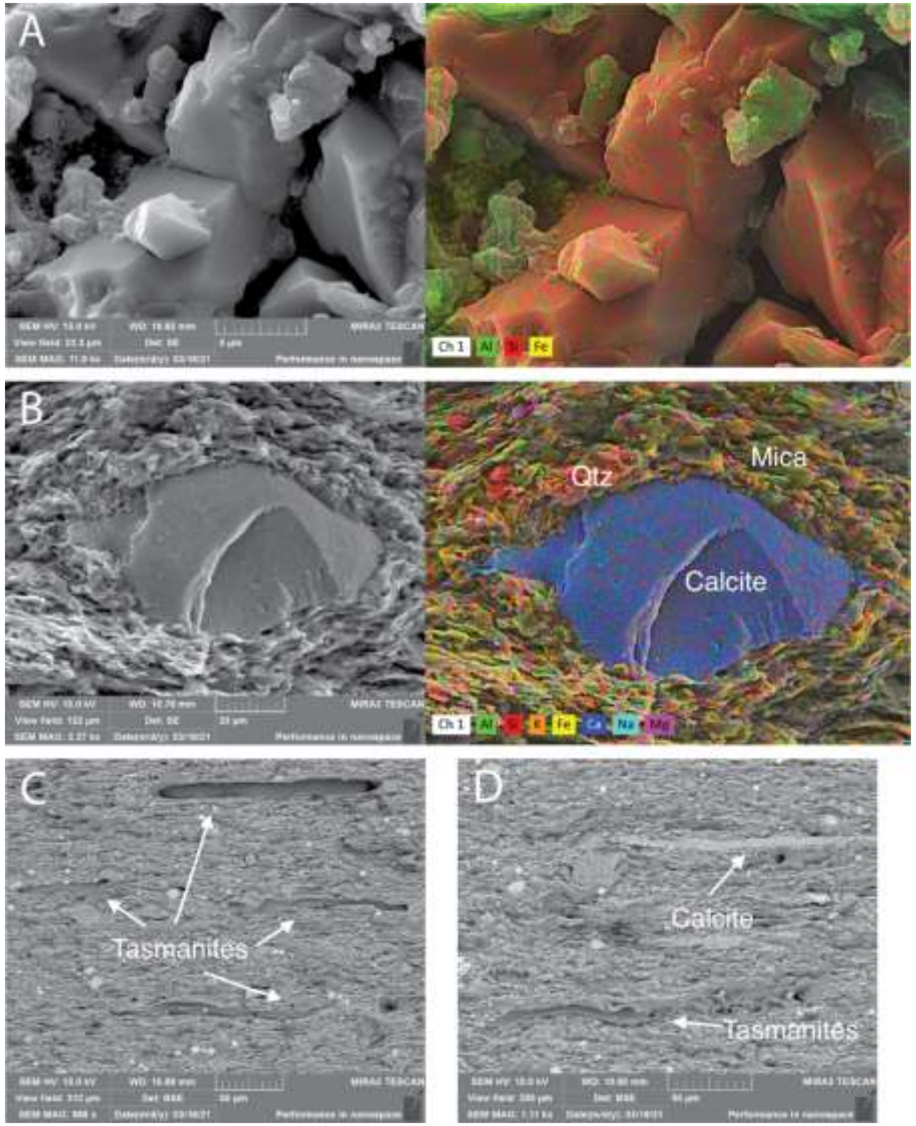


FESEM images from CMLSHISI

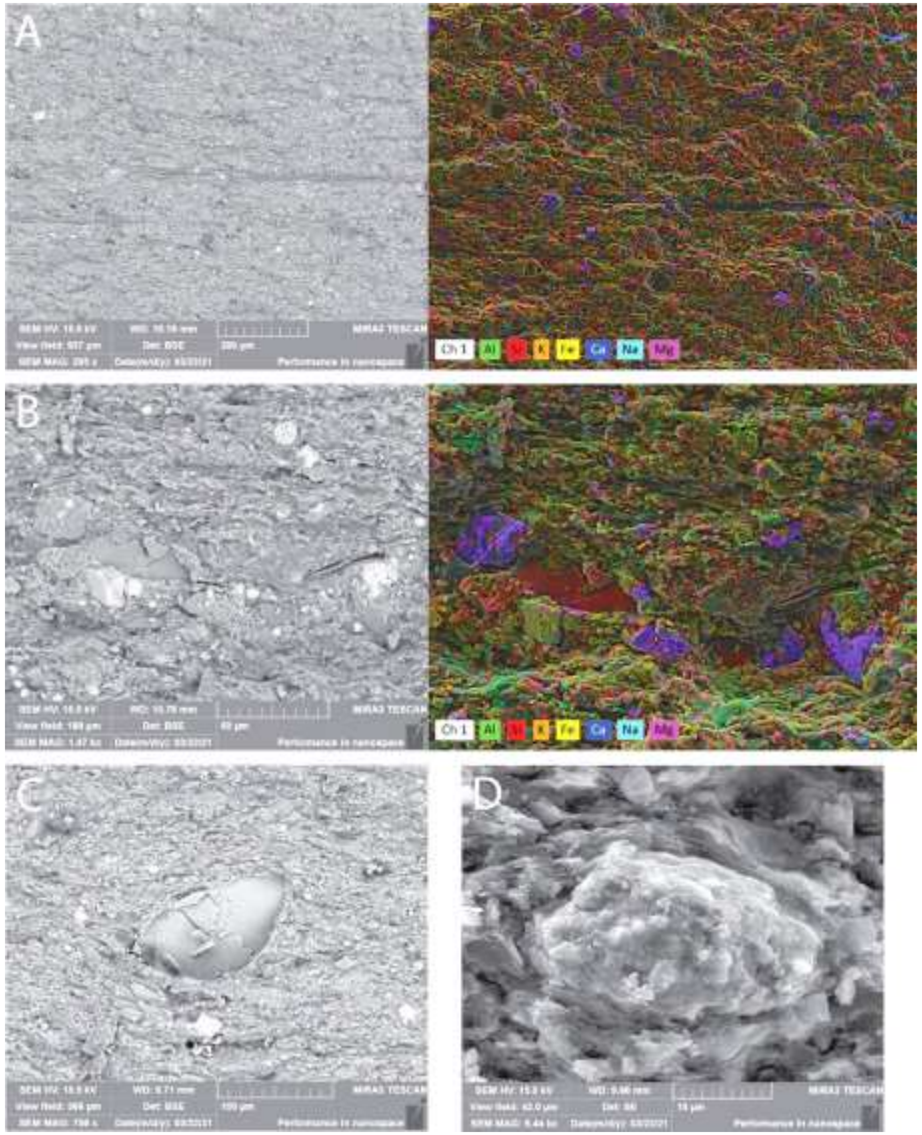


FESEM images of KOUSHISI

FESEM Analysis: Low-Silica

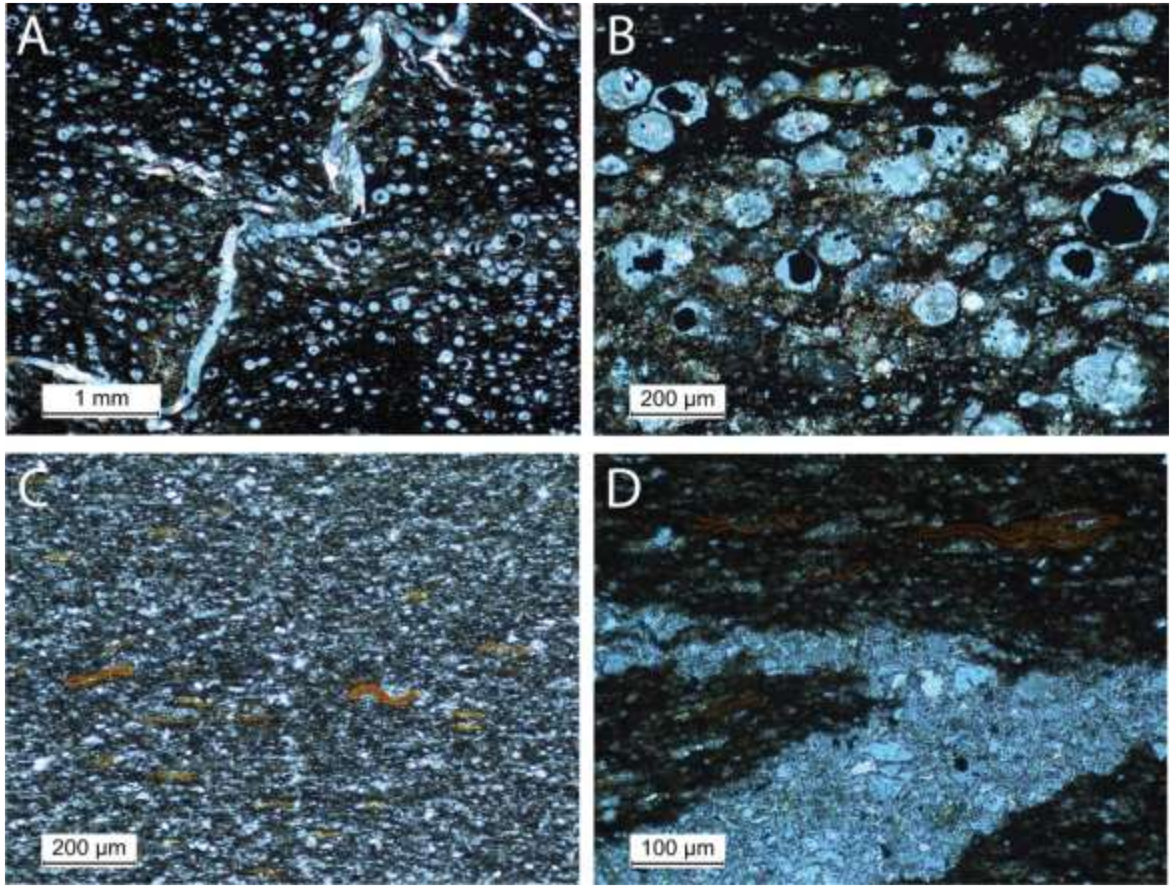


FESEM images from GSLSLOSI

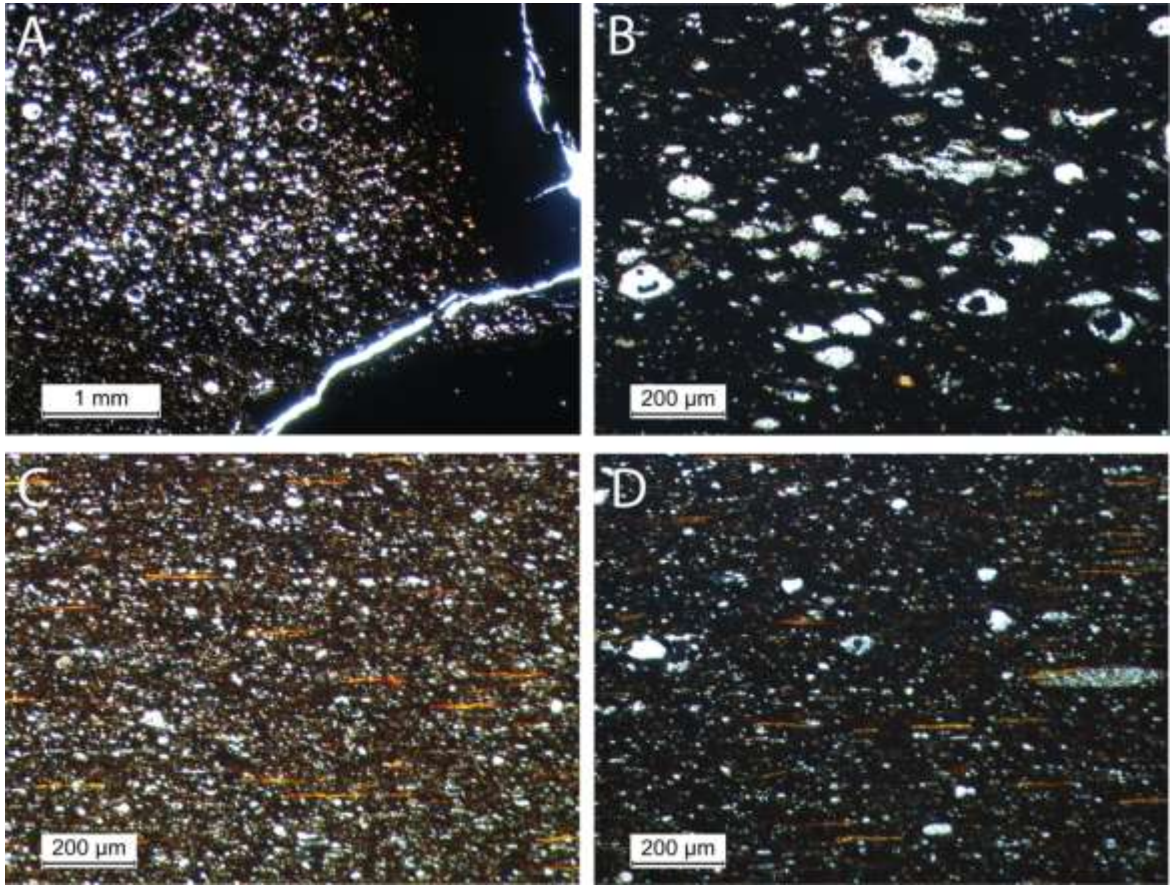


FESEM images from GSUSLOSI

Thin Section Analysis: Lower Shale

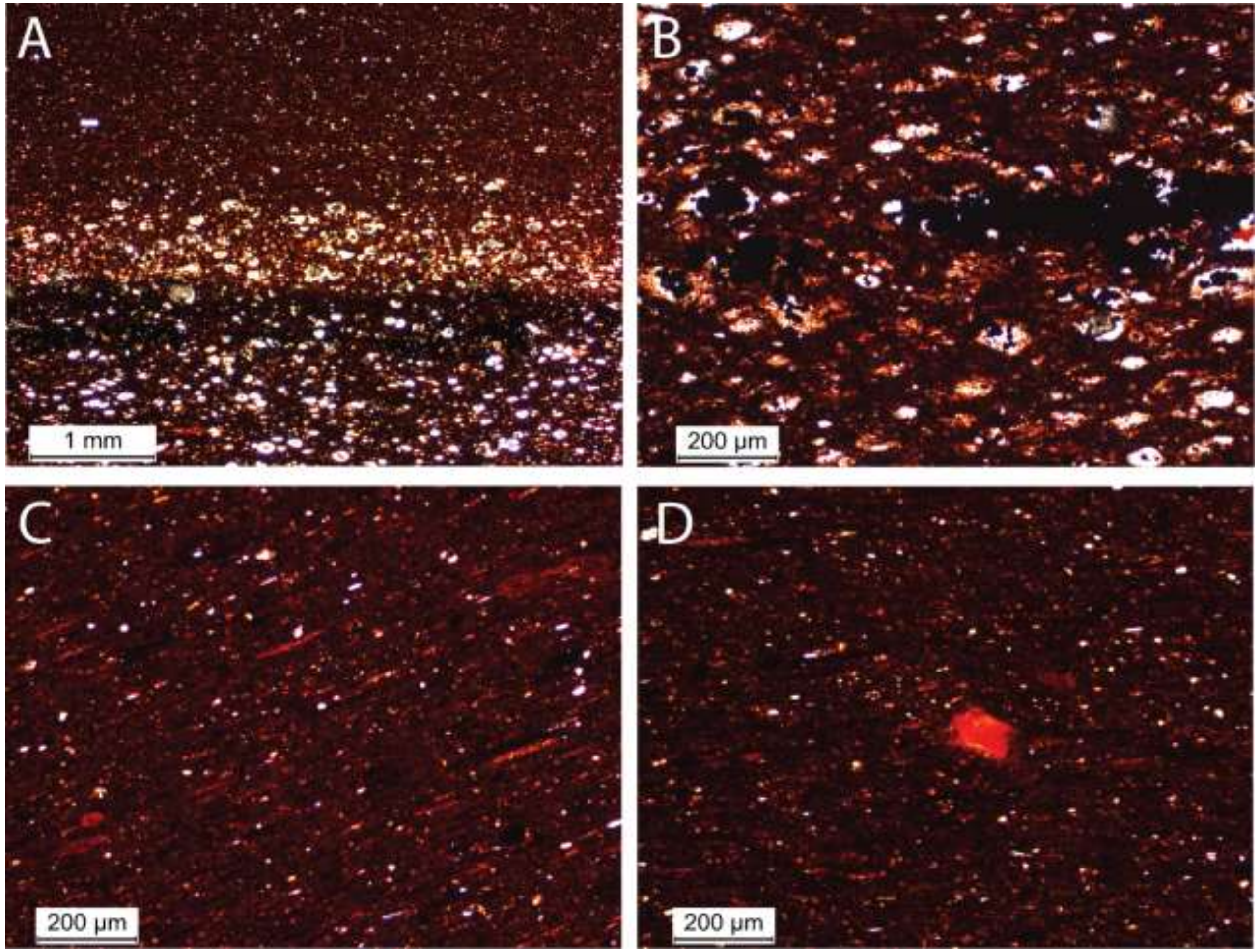


Thin section photomicrographs from the Clarion Mertes core with images from high-silica samples on top and low-silica samples on the bottom



Thin section photomicrographs from the Harvey Grey core with images from high-silica samples on top and low-silica samples on the bottom

Thin Section Analysis: Upper Shale



Thin section photomicrographs from the Koch core with images from high-silica samples on top and low-silica samples on the bottom

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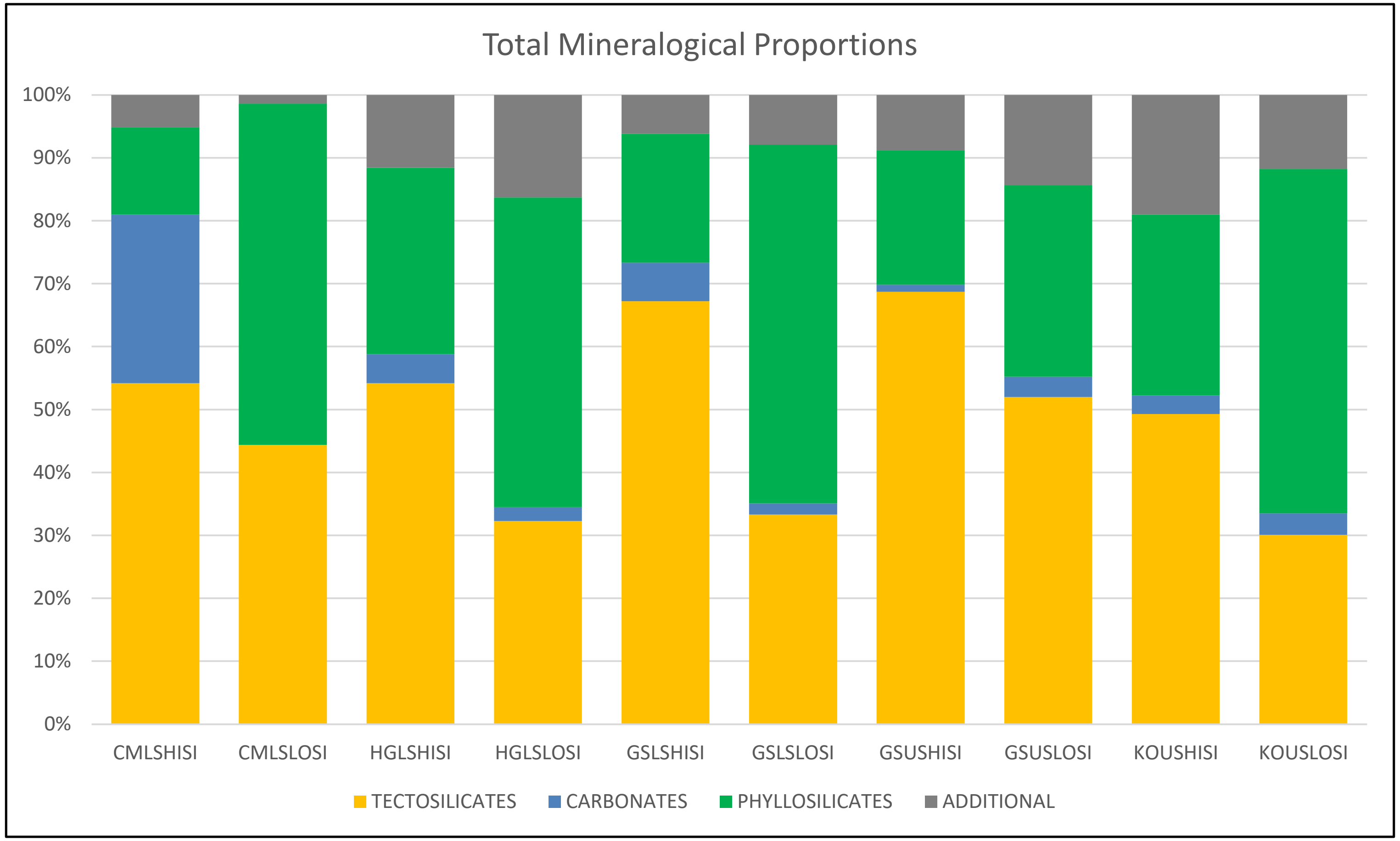
XRD Data

Sample	Sample	Sample	TECTOSILICATES			CARBONATES			PHYLLOSILICATES
Name	Core	Depth (ft)	Quartz	K-spar	Plag.	Calcite	Dolomite	Siderite	Total Clay
CMLSHISI	Clarion Mertes	7221.75	49.1	4.1	1.0	25.2	1.6	0.0	13.8
CMLSLOSI	Clarion Mertes	7210.33	32.6	7.9	3.9	Tr	Tr	0.0	54.2
HGLSHISI	Harvey Grey	9052.50	46.9	5.2	2.1	Tr	4.6	0.0	29.6
HGLSLOSI	Harvey Grey	9056.83	22.6	7.6	2.1	Tr	2.2	0.0	49.2
GSLSHISI	Gunnison State	8212.83	60.7	4.5	2.0	3.6	2.5	0.0	20.5
GSLSLOSI	Gunnison State	8210.33	24.5	5.6	3.2	0.0	1.8	0.0	57.0
GSUSHISI	Gunnison State	8144.33	62.7	4.2	1.8	Tr	1.1	0.0	21.4
GSUSLOSI	Gunnison State	8145.00	44.2	5.6	2.2	Tr	3.2	0.0	30.4
KOUSHISI	Koch	7036.58	41.7	5.4	2.2	0.6	2.3	0.0	28.8
KOUSLOSI	Koch	7030.75	21.7	6.4	2.0	Tr	3.4	0.0	54.7

XRD Data: Proportions



XRD Data Compared with Mineral Model

Sample	Sample	Sample	Normalized XRD Measurements			Mineral Model Calculations		
Name	Core	Depth (ft)	Quartz	Calcite	Total Clay	Quartz	Calcite	Illite
CMLSHISI	Clarion Mertes	7221.75	55.7	28.6	15.7	75.8	8.0	16.2
CMLSLOSI	Clarion Mertes	7210.33	37.5	0.1	62.4	3.4	0.1	96.5
HGLSHISI	Harvey Grey	9052.50	61.2	0.1	38.6	51.0	1.0	48.0
HGLSLOSI	Harvey Grey	9056.83	31.4	0.1	68.4	8.7	0.7	90.5
GSLSHISI	Gunnison State	8212.83	71.6	4.2	24.2	66.7	5.8	27.5
GSLSLOSI	Gunnison State	8210.33	30.1	0.0	69.9	7.9	0.4	91.7
GSUSHISI	Gunnison State	8144.33	74.5	0.1	25.4	69.2	1.4	29.5
GSUSLOSI	Gunnison State	8145.00	59.2	0.1	40.7	46.7	1.5	51.8
KOUSHISI	Koch	7036.58	58.6	0.8	40.5	75.4	1.6	23.0
KOUSLOSI	Koch	7030.75	28.4	0.1	71.5	24.1	2.4	73.5

Quartz Crystallinity Index Calculations

Sample Name	Sample Core	Sample Depth (ft)	TECTOSILICATES	
			Quartz wt%	Crystallinity Index
CMLSHISI	Clarion Mertes	7221.75	49.1	5.4
CMLSLOSI	Clarion Mertes	7210.33	32.6	7.3
HGLSHISI	Harvey Grey	9052.50	46.9	2.8
HGLSLOSI	Harvey Grey	9056.83	22.6	7.9
GSLSHISI	Gunnison State	8212.83	60.7	2.9
GSLSLOSI	Gunnison State	8210.33	24.5	5.0
GSUSHISI	Gunnison State	8144.33	62.7	2.9
GSUSLOSI	Gunnison State	8145.00	44.2	4.8
KOUSHISI	Koch	7036.58	41.7	3.4
KOUSLOSI	Koch	7030.75	21.7	5.8

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NO2 Physisorption Data

Process	Measurement	GSUSHISI	GSUSLOSI	GSLSHISI	GSLSLOSI
Adsorption	Pore Surface Area	0.79202 m^2/g	0.56455 m^2/g	1.437 m^2/g	1.0434 m^2/g
	Pore Volume	0.0013921 cc/g	0.0010698 cc/g	0.0080652 cc/g	0.00288 cc/g
Desorption	Pore Surface Area	0.67321 m^2/g	0.46953 m^2/g	3.3606 m^2/g	1.2238 m^2/g
	Pore Volume	0.0011354 cc/g	0.00090207 cc/g	0.0084478 cc/g	0.0026828 cc/g

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Important Conclusions

- The most silica-rich intervals of the upper and lower shales contain biogenic silica
- The biogenic silica comes from radiolarians and has been partially replaced by pyrite in roughly half of the tests. Calcite in ptygmatic fractures was also replaced by pyrite, which means that these fractures occurred and were filled before diagenesis.
- The radiolarians in these intervals are in the form of microcrystalline quartz that can be tracked by QCI calculations made with XRD data.
- Dissolution and reprecipitation of silica could be creating or preserving pore spaces within the most silica-rich parts of the shales, but more data is needed to draw this conclusion with confidence

Recommendation for Future Analysis

- Determine the resolution of location-dependent trends in detrital versus biogenic silica deposition, particularly between the shale margins and depocenters. This could be done with QCI measurements from quartz-heavy XRD data as well

- Attempt to correlate shale intervals that contain abundant biogenic silica with core samples taken from across the Williston Basin.

- Perform FESEM microscopy on the thin section samples created for this project to identify any other replacement minerals besides pyrite, as well as compare accessory minerals with those found in rough sample FESEM analysis.

- Perform physisorption analysis on as many highly siliceous shale intervals as possible from the other core samples used in this project and throughout the Williston Basin. A greater sample size is needed to determine the existence of the preliminary pore volume and surface area trends observed in the data gathered in this project.

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