Characterizing Diagenetic Silica in the Upper and Lower Shales of the Bakken Formation, Williston Basin, North Dakota

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M.S. Geology Candidate Spring 2021 MUDTOC Fall 2020 Meeting

Outline



• Bakken Formation / Silica Diagenesis Introduction

Core Overview

XRF Data

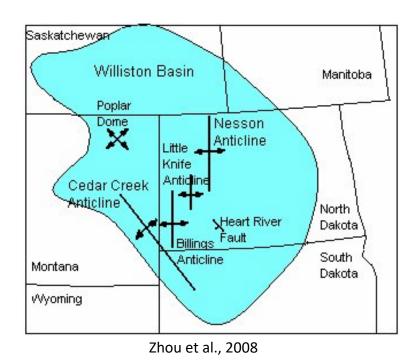
Mineral Model Core Descriptions

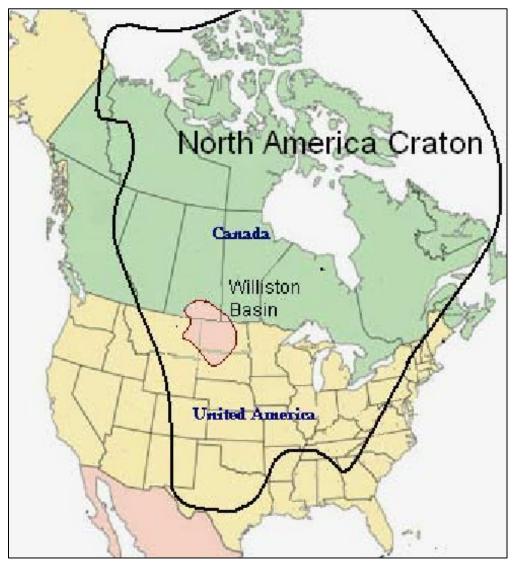
Next Steps

The Williston Basin



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

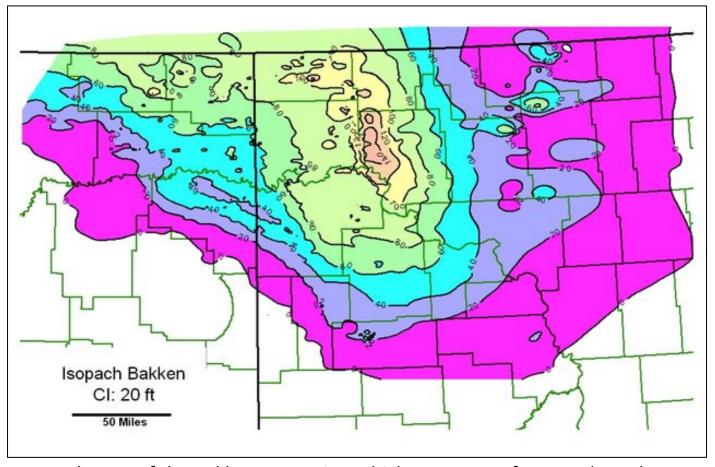




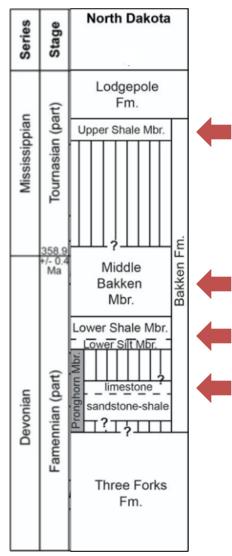
Zhou et al., 2008

The Bakken Formation





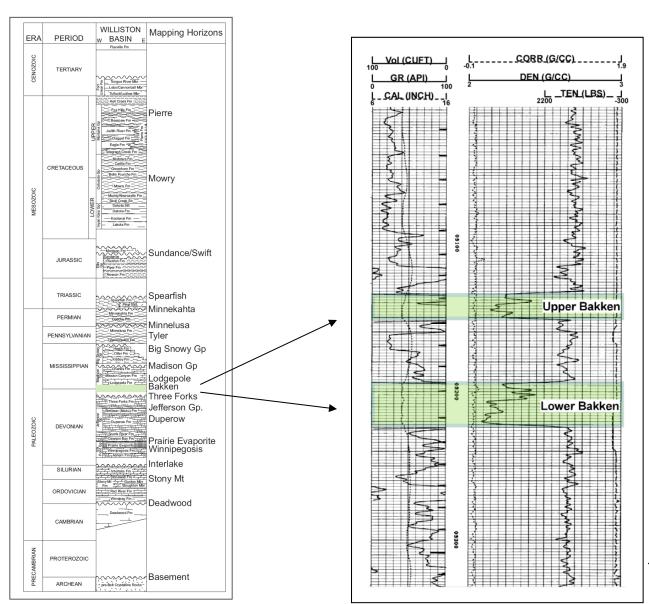
Isopach Map of the Bakken Formation. Thickness ranges from wedge-edge to over 140 feet. From Sonnenberg et al., 2011



Sandberg et al., 1988

The Bakken in Well Logs





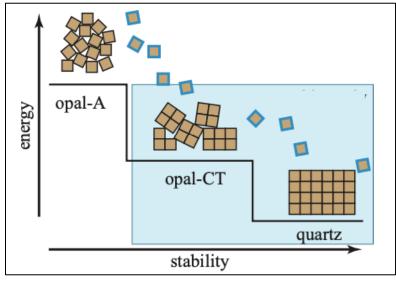
Lear Petroleum
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Silica Diagenetic Sequence



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

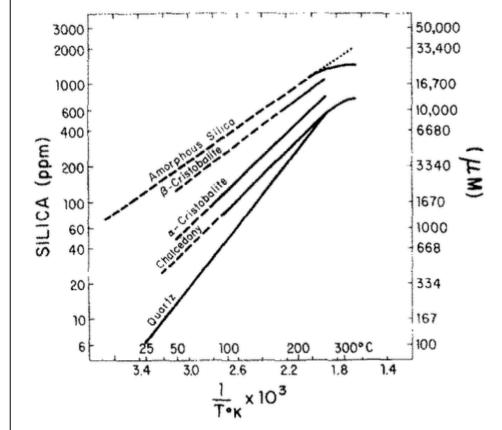


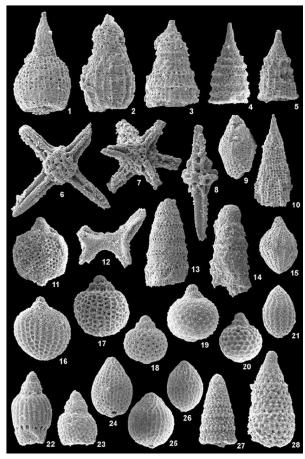
Fig. 1. Solubilities of the various silica phases along the two-phase curve, water plus vapor. Plotted as log concentration vs. reciprocal of absolute temperature, after FOUR-NIER (1973, Fig. 2).

From Kastner et al., 1977.

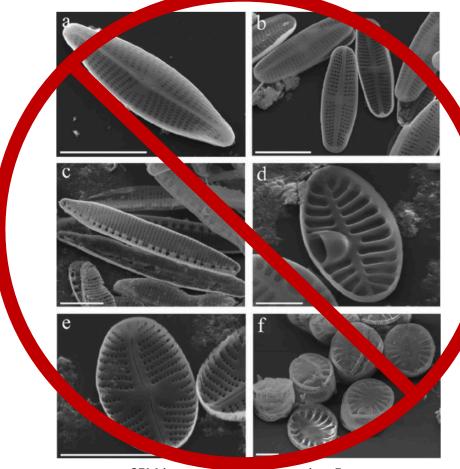
Before Deposition



Diatoms form frustules (shells) and radiolarians form tests (skeletons) out of amorphous silica from dissolved silica in water.



SEM images of Middle Jurassic radiolaria. From Robin et al., 2010.

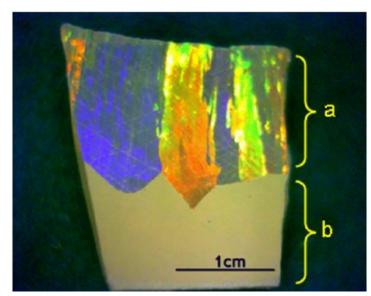


SEM images of diatom species. From Brinkmann et al., 2014.

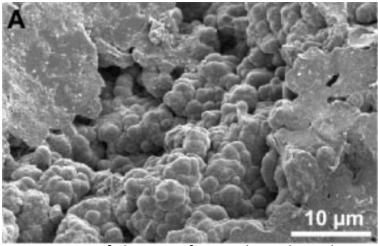
Opal-A



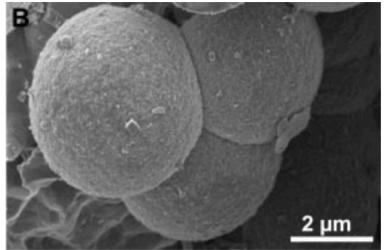
Opal: A hydrated amorphous form of silica, with water content usually ranging from 6-10%. Technically a mineraloid and not a mineral because it is not crystalline.



Opal with ordered (a) and disordered (b) sphere packing. Masalov et al., 2011



SEM image of clusters of smooth opal-A spheres from Steamboat Springs, Nevada. Lynn et al., 2007

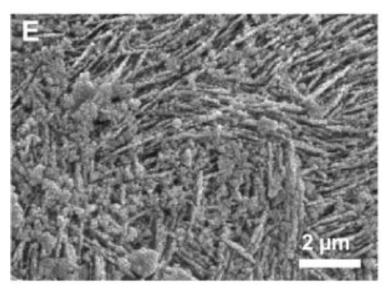


SEM image of opal-A spheres with rough surfaces, indicating the beginning of the opal-A to opal-CT transition. Lynn et al., 2007

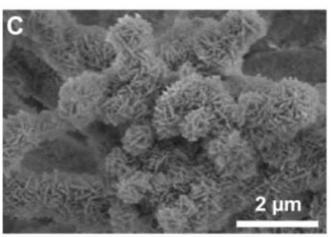
Opal C-T



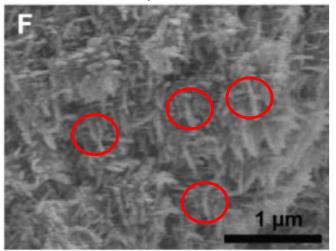
Opal C-T: A microcrystalline form of silica, which consist of clusters of stacked cristobalite and tridymite. These two polymorphs of silica form nanocrystalline blades that cluster into spheres called lepispheres.



SEM image of detailed close-up view of blades of opal C-T. Lynn et al., 2007



SEM image of newly forming opal C-T bladed lepispheres from Sinter Island, New Zealand. Lynn et al., 2007



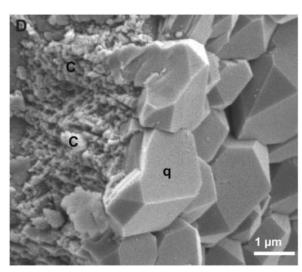
SEM image of aligned nanostructures forming as opal C-T lepispheres begin the transition to opal-C. Lynn et al., 2007

Microcrystalline Quartz

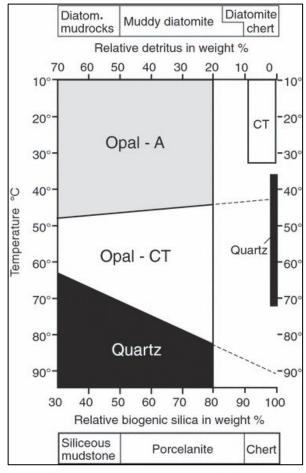


Microcrystalline Quartz:

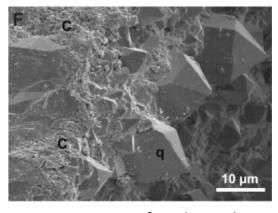
If the conditions are suitable - i.e. if we have a high enough temperature in combination with a low enough silica concentration - quartz begins to form



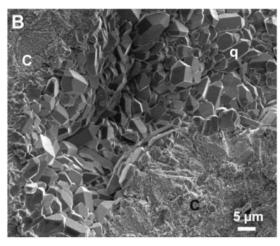
SEM image of opal-C and microcrystalline quartz. Sinter Island. Lynn et al., 2007



Relationship between lithology, silica phase, detrital content of sediment and temperature or burial depth. Behl, 2010



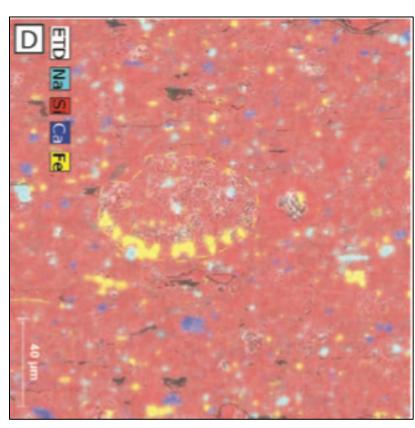
SEM image of opal-C and microcrystalline quartz. Steamboat Springs. Lynn et al., 2007



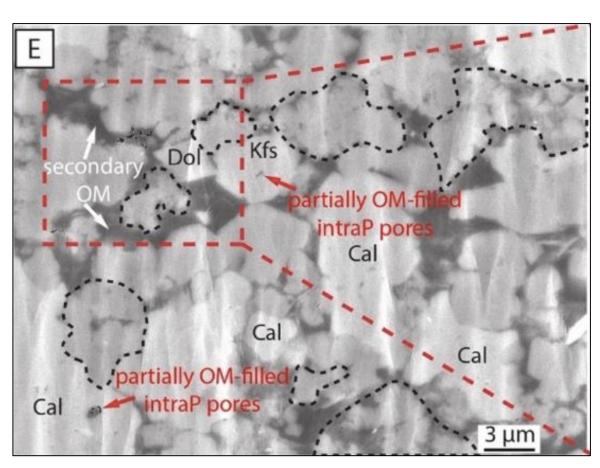
SEM image of opal-C and microcrystalline quartz. Opal Mound. Lynn et al., 2007

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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Clarion Mertes 8 boxes, 61ft



Koch 7 boxes, 50 ft



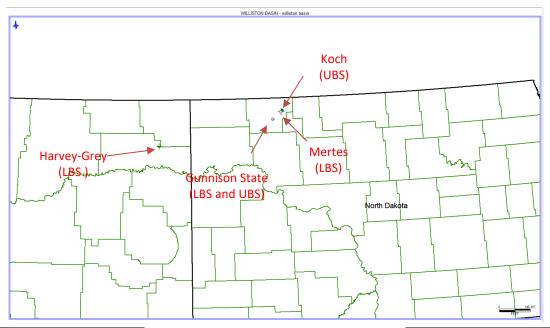
Harvey Grey 7 boxes, 58ft

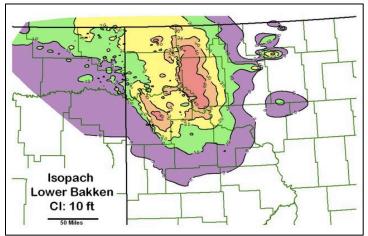


Gunnison State 16 Boxes, 122ft

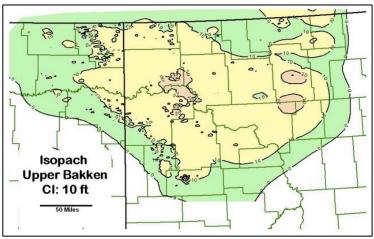
Core Overview: Locations







Sonnenberg et al., 2011

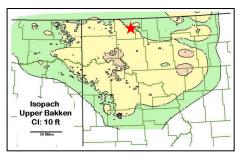


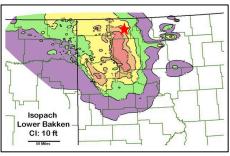
Sonnenberg et al., 2011

Core Overview: Gunnison State



- 3/16 boxes used,
 14.3ft of LBS and
 2.25ft of UBS XRF'd
- XRF measurements taken at 2-inch intervals



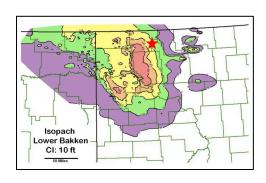




Core Overview: Clarion Mertes



- 3/8 boxes used,
 ~17.6ft XRF data
- XRF measurements taken at 3-inch intervals for other cores to save time

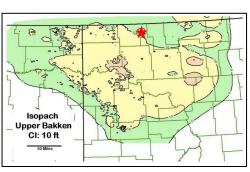


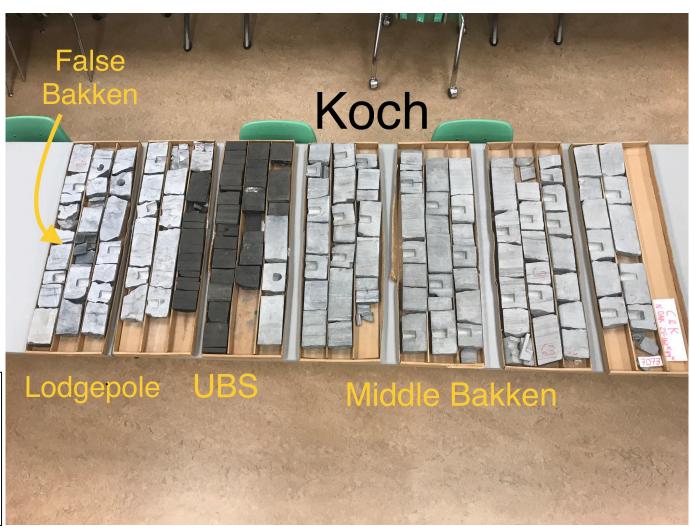


Core Overview: Koch



- 2/7 boxes used, 9ft of XRF data
- The "False Bakken"
 can be seen in this
 core, which shows
 up in logs as a
 gamma ray spike in
 certain parts of the
 basin

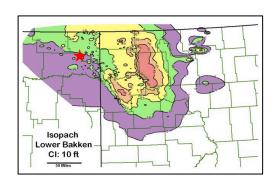




Core Overview: Harvey Grey



- 2/7 boxes, 7.5ft of XRF data collected from the LBS
- Located in a different part of the basin than the other 3 cores, provides some regional variety





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Clarion Mertes 74 scan points 17.6 feet

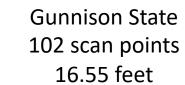


Koch 35 scan points 9 feet



Harvey Grey 33 scan points 7.5 feet

244 total scan points



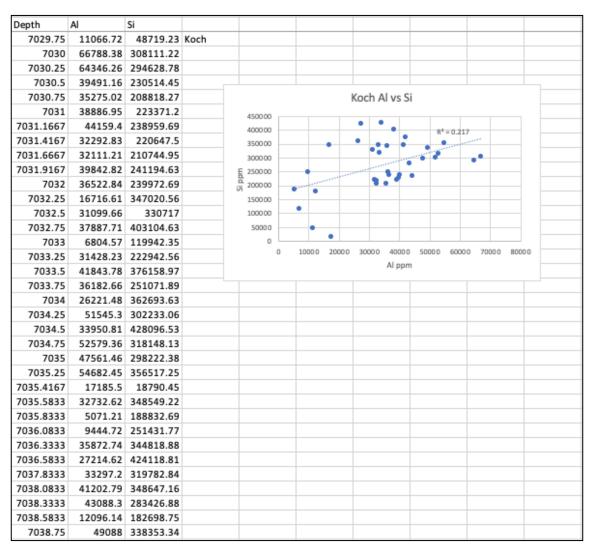
XRF Data: Raw Data



-																													
Α	В	C D		F G	H		К	L	М	N	0	P	Q	R	S	T	U	V	W	X		Z	AA	AB	AC	AD	AE	AF	
dex	Reading No		16-	tion Units	Sigma Value Sequence			o Error Zr		r Error Sr		Sr Error U		U Error R		Error Th		Error Pb		Error Au		Error Se					-	Hg Error	Zn
18		8 7208.9167 8/28/20 16:14 7 7209.1667 8/28/20 16:10		180 ppm 180 ppm	2 Final 2 Final	-8mm	26.56 211.26	3.27 4.51	225.59 99.35	5.22 3.47	48.26 47.91	2.6 2.55	22.15	5.66	85.89 114.77	3.04	17.99	3.56	15.33 13.03	4.54 6.94	0		5.25		9.68 91.86	3.69 8.22	0		\vdash
16				180 ppm	2 Final	-8mm	879.82	8.84	136.65	4.12	58.49	2.68	35.19	6.17	115.26	3.3	10.69	3.19	17.62	4.78	0		26.94	3.57	129.11	6.78	- 0		+
15		5 7209.6667 8/28/20 16:00		180 ppm	2 Final	-8mm	196.9	4.68	108.47	3.83	39.52	2.53	33.13	0.17	121.01	3.98	0	3.13	22.02	7.4	0		20.54	3.37	47.4	7.53	0		_
14	_			180 ppm	2 Final	-8mm	276.68	5.84	113.59	4.16	76.3	3.21	44.27	6.63	98.55	3.3	9.47	3.53	57.84	7.52	0		78.2	5.54	99.41	7.56	0		+
13	13			180 ppm	2 Final	-8mm	121.7	3.92	104.25	3.89	34.19	2.49	0		105.56	3.84	0		0		0		0		0		0		
12	1	2 7210.25 8/28/20 15:41	TestAll Geo	180 ppm	2 Final	-8mm	283.62	6.33	40.62	3.01	30.64	2.57	0		50.99	2.96	0		150.46	14.36	0		0		251.91	16.62	0		
11	11	1 7210.3333 8/28/20 15:37	TestAll Geo	180 ppm	2 Final	-8mm	140.22	4.05	100.51	3.75	41.06	2.59	0		114.83	3.91	0		19.43	7.3	0		0		35.34	7.12	0		
10	10	0 7210.5833 8/28/20 15:31	TestAll Geo	180 ppm	2 Final	-8mm	164.29	4.23	99.32	3.64	39.15	2.48	0		95.27	3.47	0		52.88	9.1	0		0		123.98	10.41	0		
9		9 7210.8333 8/28/20 15:25		180 ppm	2 Final	-8mm	93.12	3.16	124.5	4.21	42.74	2.54	52.57	7.04	117.25	3.61	11.08	3.46	25.43	5.42	0		16.53		36.67	5.11	12.4	7.35	j .
8		8 7211.0833 8/28/20 15:12		180 ppm	2 Final	-8mm	97.93	2.81	128.41	3.77	62.43	2.58	67.65	6.51	123.96	3.25	19.42	3.3	11.93	3.92	0		7.63	2.54	14.25	3.33	0		\perp
7		7 7211.3333 8/28/20 15:03		180 ppm	2 Final	-8mm	97.47	2.82	129.48	3.78	57.94	2.51	73.48	6.63	123.2	3.26	14.15	3.09	9.64	3.85	6.98	4.24	11.96		11.24	3.16	0		
- 6		6 7211.5833 8/28/20 14:58		180 ppm	2 Final	-8mm	50.67	2.26	118.46	3.63	72.11	2.71	83.13	6.55	106.1	2.98	11.79	2.91	10.69	3.72	0		4.1	2.34	0	2.11	9.27	5.42	4
- 5		5 7211.8333 8/28/20 14:50		180 ppm	2 Final	-8mm	72.05	2.64	120.12	3.92	114.96	3.49	83.83	6.94	108.51	3.17	12.03	3.08	11.74	4.05	0		8.69	2.76	6.13	3.14	0		⊢
4		4 7212.0833 8/28/20 14:31		180 ppm	2 Final	-8mm	44.93	2.17	137.86	3.77	71.15	2.64	70.06	6.18	107.15	2.95	13.82	2.94	10.45	3.68	0		6.91	2.44	5.38	2.83	0		\vdash
2		3 7212.3333 8/28/20 14:13 2 7212.4167 8/28/20 14:01		180 ppm 180 ppm	2 Final 2 Final	-8mm -8mm	459.01 279.95	6.09 5.9	114.85 71.98	3.48	41.68 40.56	2.13	69.88	6.24	113.37 88.91	3.02	12.26	2.89	10.4 66.21	3.69 10.37	0	-	7.24		5.03 125.94	2.82 11.38	0		-
		1 7212.6667 8/28/20 13:45		180 ppm 180 ppm	2 Final	-8mm	412.46	9.09	90.71	4.62	41.06	3.31	0		95.06	4.54	0		106.43	14.44	0		0		105.62	14.46	0		+
24		4 7212.9167 8/26/20 18:43		180 ppm	2 Final	-8mm	222.66	5.65	158.54	5.11	27.24	2.51	0		62.58	3.28	0		63.05	11.15	0		0		84.79	11.28	0		\vdash
23	_	3 7213.1667 8/26/20 18:39		180 ppm	2 Final	-8mm	85.92	3.62	266.97	6.1	32.23	2.45	0		37.57	2.42	0		28.35	7.79	0		0		19.66	7.05	0		+
22		2 7213.4167 8/26/20 18:35		180 ppm	2 Final	-8mm	306.36	7.02	81.61	4.12	45.63	3.21	0		121.25	4.75	0		72.53	12.23	0		0		44.31	10.92	0		+
21		1 7213.6667 8/26/20 18:30		180 ppm	2 Final	-8mm	635.05	7.81	70.99	2.83	45.38	2.46	69.15	6.52	76.57	2.77	8.48	3.2	48.38	6.32	0		29.68	3.75	33.13	5.36	0		\perp
20		0 7213.9167 8/26/20 18:25		180 ppm	2 Final	-8mm	385.59	6.57	111.21	3.98	38.12	2.39	70.19	7.14	105.46	3.38	13.47	3.39	9.12	4.15	0		0		0	-	0		\perp
19	19	9 7214.1667 8/26/20 18:18	TestAll Geo	180 ppm	2 Final	-8mm	278.76	5.54	77.31	3.33	25.9	2.18	0		91.19	3.46	0		11.5	6.64	0		0		0		0		
18	18	8 7214.4167 8/26/20 18:13	TestAll Geo	180 ppm	2 Final	-8mm	115.8	4.14	46.91	3.19	41.89	2.91	0		48.71	2.92	0		26.08	8.31	0		0		0		0		Т
17	1	7 7214.6667 8/26/20 18:09	TestAll Geo	180 ppm	2 Final	-8mm	226.02	5.73	54.87	3.39	22.6	2.41	0		61.53	3.32	0		36.23	9.42	0		0		19.95	8.32	0		
16	16	6 7214.75 8/26/20 18:02	TestAll Geo	180 ppm	2 Final	-8mm	75.54	4.03	106.01	4.77	45.46	3.35	0		35.77	2.86	0		29.75	9.6	0		0		34.3	9.31	0		
15		5 7214.9167 8/26/20 17:57		180 ppm	2 Final	-8mm	426.09	7.32	59.9	3.18	33.86	2.49	0		76.38	3.3	0		42.05	8.76	0		0		20.9	7.66	0		
14		4 7215.1667 8/26/20 17:50		180 ppm	2 Final	-8mm	296.48	5.4	68.87	3.02	39.24	2.37	0		71.15	2.89	0		55.88	8.42	0		0		30.16	7.52	0		
13	_	3 7215.4167 8/26/20 17:44		180 ppm	2 Final	-8mm	453.38	6.96	61.85	2.77	40.1	2.42	74.04	6.83	77.26	2.88	7.53	3.24	45.4	6.26	0		17.51		28.55	5.29	0		\perp
12		2 7215.6667 8/26/20 17:31		180 ppm	2 Final	-8mm	321.52	5.77	64.41	3	36.55	2.35	0		75.24	3.02	0		77.58	9.27	0		0		77.66	9.39	0		
11		1 7215.9167 8/26/20 17:26		180 ppm	2 Final	-8mm	343.21	5.94	65.93	3	30.32	2.19	0		85.71	3.2	0		54.77	8.48	0		0		37.57	7.82	0		-
10		0 7216.5833 8/26/20 17:21		180 ppm	2 Final	-8mm	358.53	6.1	70.62	3.09	33.49	2.27	0		78.89	3.08	0		54.29	8.44	0		0		41.58	7.91	0		-
9		9 7216.8333 8/26/20 17:15		180 ppm	2 Final	-8mm	360.13	6.19	62.15	2.97	25.3	2.09	0		68.53	2.93	0		40.7	8.06	0	-	0		28.82	7.29	0		\vdash
		8 7217.0833 8/26/20 17:09		180 ppm	2 Final	-8mm	307.66	6.05	63.02	3.2	30.68	2.39	64.00		70.71	3.17	10.73	2.21	57.56	9.41	0		10.00	2.51	33.97	8.53	0		-
		7 7217.3333 8/26/20 16:57 6 7217.5833 8/26/20 16:52		180 ppm 180 ppm	2 Final 2 Final	-8mm -8mm	508.65 287.38	7.32 5.28	59.81 52.68	2.74	32.85 24.7	2.25	64.83	6.53	70.36 62.75	2.77	10.73	3.31	34.12 30.51	5.75 7.32	0	-	18.86		19.45 17.46	4.72 6.35	0		+
		5 7217.8333 8/26/20 16:45		180 ppm	2 Final	-8mm	301.5	5.28	57.89	2.72	26.65	2.01			65.5	2.75	0		46.44	7.88	0		0		22.13	6.95	0		+
4		4 7218.0833 8/26/20 16:34		180 ppm	2 Final	-8mm	219.96	4.7	65.24	2.99	31.26	2.22	ď		64	2.76	0		53	8.37	0		0		29.23	7.54	0		+
3		3 7218.3333 8/26/20 16:28		180 ppm	2 Final	-8mm	193.01	4.36	61.15	2.89	28.33	2.12	9		60.82	2.71	0		55.55	8.32	0		0		44.94	7.94	0		+
2		2 7218.5833 8/26/20 16:22		180 ppm	2 Final	-8mm	190.91	4.19	40.97	2.45	23.72	1.94	0		47.29	2.35	0		38.02	7.33	0		0		28.69	6.78	0		+
1		1 7219.0833 8/26/20 16:17		180 ppm	2 Final	-8mm	173.44	5.17	53.1	3.45	27.12	2.62	0		93.1	4.12	0		36.65	9.56	22.75	12.42	0		27.74	8.78	0		+
32		2 7219.3333 8/24/20 18:00		180 ppm	2 Final	-8mm	205.29	4.51	57.22	2.84	30.01	2.17	0		61.95	2.74	0		40.15	7.82	0		0		44.65	7.59	0		+
31		1 7219.5833 8/24/20 17:55		180 ppm	2 Final	-8mm	216.1	4.84	55.71	2.94	27.73	2.21	0		59.53	2.82	0		45.78	8.54	0		0		60.19	8.61	0		\perp
30		0 7219.8333 8/24/20 17:51		180 ppm	2 Final	-8mm	268.29	5.41	49.3	2.84	28.19	2.23	0		52.31	2.68	0		32.58	7.98	0		0		49.12	7.94	0		Τ
29	29	9 7220.0833 8/24/20 17:44	TestAll Geo	180 ppm	2 Final	-8mm	497.86	6.91	55.45	2.54	35.26	2.2	60.53	6	60.36	2.46	9.29	3.07	34.62	5.52	0		21.88	3.41	25.21	4.68	0		
28	28	8 7220.3333 8/24/20 17:39	TestAll Geo	180 ppm	2 Final	-8mm	268.74	5.37	50.48	2.83	31.41	2.29	0		57.39	2.74	0		34.65	7.78	0		0		23.68	6.98	0		
27				180 ppm	2 Final	-8mm	460.83	6.88	55.53	2.61	37.66	2.32	86.26	6.84	67.66	2.65	6.4	3.01	33.63	5.61	0		21.42		34.99	5.06	0		Γ
26				180 ppm	2 Final	-8mm	407.81	6.79	57.74	2.67	34.51	2.28	279.49	10.48	85.88	2.99	7.84	3.12	25.01	5.22	0		19.47		16.8	4.3	0		Ĺ
25				180 ppm	2 Final	-8mm	336.35	6.08	66.69	3.12	31.22	2.29	0		70.46	3.02	0		59.5	8.97	0		0		72.18	9.18	0		1
24				180 ppm	2 Final	-8mm	154.13	4.29	36.62	2.7	36.45	2.52	0		56.2	2.84	0		38.38	8.43	0		0		45.58	8.18	0		1
23				180 ppm	2 Final	-8mm	148.14	4.56	38.02	2.99	38.62	2.8	0	****	92.35	3.93	0		33.84	9.46	21.41	11.51	0	2.57	26.7	8.39	0		+
22				180 ppm	2 Final	-8mm	173.05	3.47	70.92 22.83	2.57 1.72	50.83 37.27	2.36	425.52 35.46	11.15 4.17	95.66 27.26	2.8 1.53	7.16 3.87	2.77	26.06 18.49	4.68 3.92	18.57	7.3	19.09 12	2.97	31.1 17.3	4.23 3.36	7.60		ŀ
21	_			180 ppm	2 Final 2 Final	-8mm	73.91 72.94	2.31				1.95	35.46 35.14		26.68	1.53		2.23		3.92	0	-				3.36	7.69	4.82	4
19				180 ppm 180 ppm	2 Final	-8mm	105	3.41	22.83 37.03	1.72 2.5	35.99 22.15	1.93 1.99	33.14	4.16	38.46	2.27	4.19	2.24	15.75 22.42	7.21	0		14.24	2.36	18.15 20.6	6.42	0		+
19				180 ppm 180 ppm	2 Final	-8mm	392.38	5.8	82.35	2.97	34.89	2.1	1100.67	18.88	213.5	4.61	13.37	3.56	29.31	5.36	55.74	9.78	18.61	3.42	17.21	4.31	0		+
17				180 ppm	2 Final	-8mm	235.22	4.73	70.65	2.99	28.66	2.09	1100.67	40.00	67.3	2.78	13.37	3.30	46.47	7.99	0	2.70	10.01		42.48	7.53	0		+
16				180 ppm	2 Final	-8mm	235.96	5.11	74.71	3.3	33.25	2.38	0		70.88	3.08	0		45.02	8.55	0	-	0		34.45	7.33	0		+
15	_			180 ppm	2 Final	-8mm	332.52	5.11	58.49	2.66	34.65	2.25	55.24	5.95	55.47	2.43	8.31	3.07	30.29	5.49	0		25.02		20.58	4.56	0		+
14				180 ppm	2 Final	-8mm	265.81	4.96	66.26	2.88	28.12	2.05	0	5.55	65.46	2.71	0	3.47	48.14	7.94	0		0		35.79	7.3	0		\dagger
13	_			180 ppm	2 Final	-8mm	405.01	6.73	67.62	2.89	36.43	2.36	82.6	7.06	72.74	2.83	8.54	3.38	57.82	6.98	0		27.48		37.7	5.94	0		\dagger
								2.10									200				-	_	21.70		2111				#

XRF Data: Al vs Si Correlations

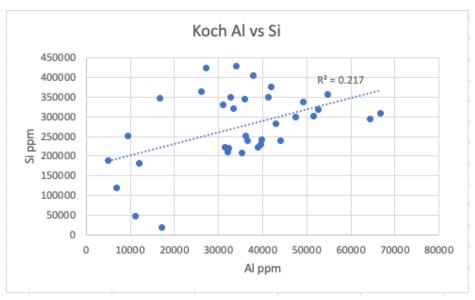


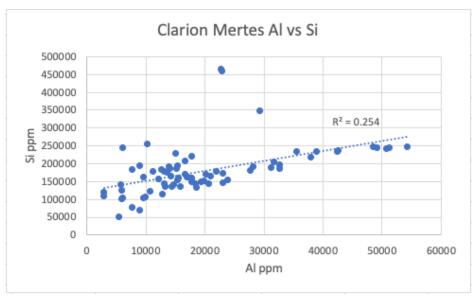


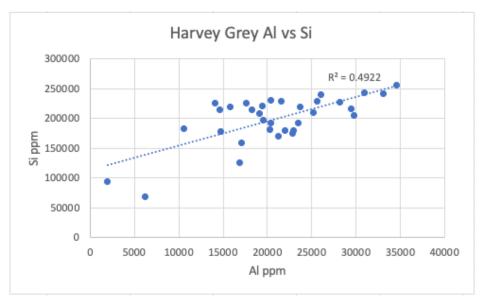
[&]quot;Aluminum is highly useful as a detrital or terrestrial proxy due to its relative diagenetic stability and its presence in clay minerals and other silicates" (Arthur & Dean, 1991)

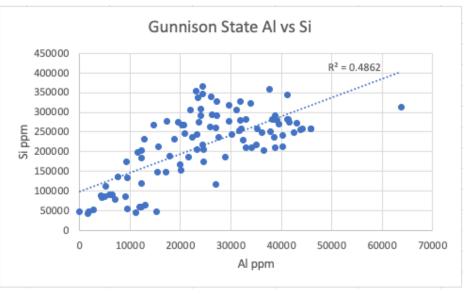
XRF Data: Al vs Si Correlations







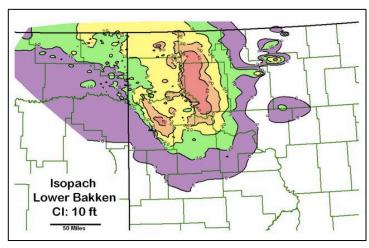




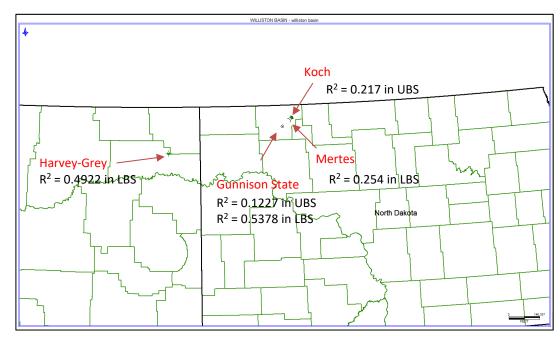
XRF Data: Al vs Si Correlations on a Map

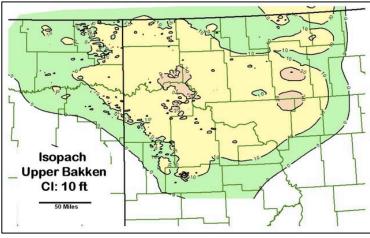


- UBS R² values are both very low in the Koch and Gunnison State wells
- LBS R² values are more sporadic and don't seem to show a consistent pattern between depocenter and margin



Sonnenberg et al., 2011

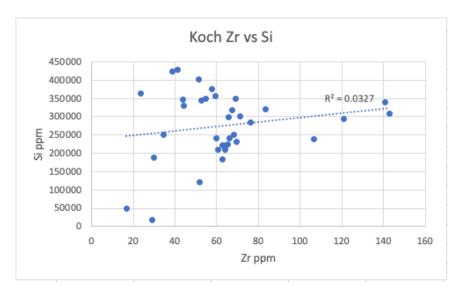


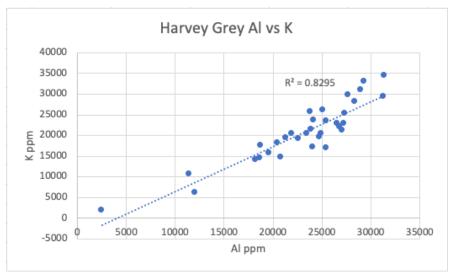


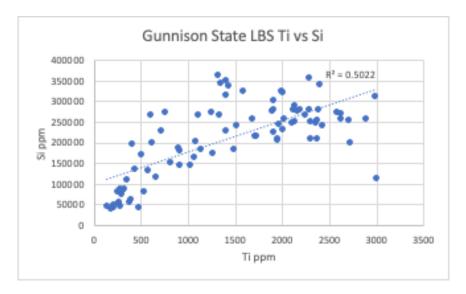
Sonnenberg et al., 2011

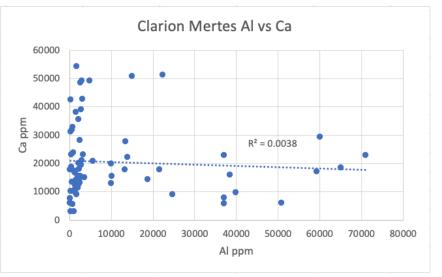
XRF Data: More Cross-plots











Outline



• Bakken Formation / Silica Diagenesis Introduction

Core Overview

XRF Data

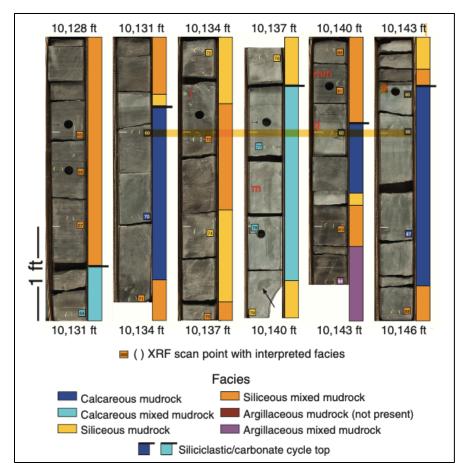
Mineral Model Core Descriptions

Next Steps

Mineral Model: Concept



- Quartz Calcite Illite model used in Nance and Rowe 2015
- "Some mineral content can be estimated with XRF data from theoretical relationships between elemental abundance and mineral abundances for minerals, whose compositions are strictly defined stoichiometrically (e.g., calcite and quartz). For illite, average K and Si contents reduced from numerous published analyses are useful for estimating illite abundances from measurements of K."



Nance and Rowe 2015

Mineral Model: Calculations

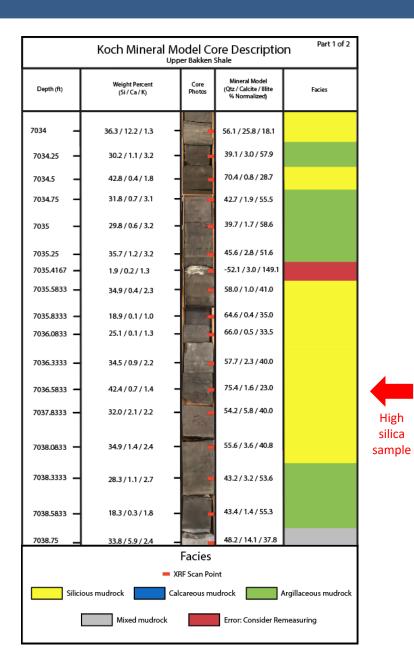


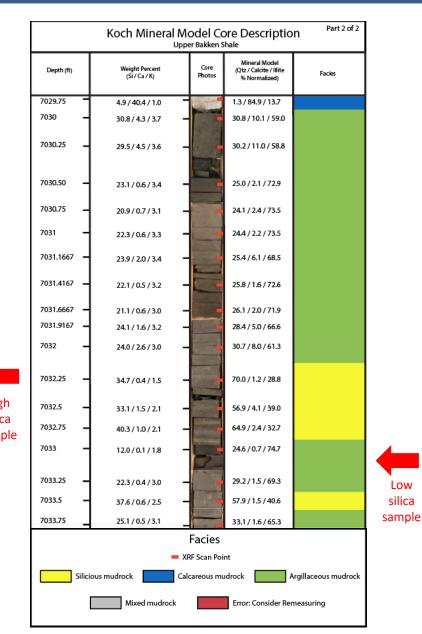
A	В	C	D	E	F	G	Н		J	K	L	M	N	0	Р	Q	R	S	T	U	1000
mple Depth (ft)	Si (ppm)	Ca (ppm)	K (ppm)	*	Si (wt %)	Ca (wt %)	K (wt %)	~	Calcite (%)	Illite (%)	%Simine	%Shotal - %Shillite	Quartz (%)	₩	Total of Calcite, Illite and Quartz	Quartz Normalized	Calcite Normalized (%)	Illite Normalized (%)	CHECK	Facies XRF (>50%)	
7029.75	48719 23	403973.88	9854.96		4.9	40.4	1.0		101.0	16.3	4.1	0.7	1.6		118.9	1.3	84.9	13.7	100.0		
7030		42567.95	37413.06		30.8	4.3	3.7		10.6	62.0	15.7	15.1	32.4		105.1	30.8	10.1	59.0	100.0		
7030.25		44835.37	36119.72		29.5	4.5	3.6		11.2	59.9	15.1	14.3	30.7		101.8	30.2	11.0	58.8	100.0		
	230514.45	6324.4	33698.18		23.1	0.6	3.4		1.6	55.9	14.1	8.9	19.1		76.6	25.0	2.1	72.9	100.0		
7030.75	208818.27	6812.83	31058.58		20.9	0.7	3.1		1.7	51.5	13.0	7.9	16.9		70.1	24.1	2.4	73.5	100.0		
7031	223371.2	6215.83	33061.77		22.3	0.6	3.3		1.6	54.8	13.8	8.5	18.2		74.6	24.4	2.1	73.5	100.0		
7031.166667	238959.69	20062.42	33850.99		23.9	2.0	3.4		5.0	56.1	14.2	9.7	20.8		82.0	25.4	6.1	68.5	100.0		
7031.416667	220647.5	4507.46	31772.13		22.1	0.5	3.2		1.1	52.7	13.3	8.8	18.8		72.6	25.8	1.6	72.6	100.0		
7031.666667	210744.95	5524.92	30132.7		21.1	0.6	3.0		1.4	50.0	12.6	8.5	18.1		69.4	26.1	2.0	71.9	100.0		
7031.916667	241194.63	16133.74	32182.11		24.1	1.6	3.2		4.0	53.4	13.5	10.6	22.8		80.2	28.4	5.0	66.6	100.0		
7032	239972.69	25851.26	29764.89		24.0	2.6	3.0		6.5	49.4	12.5	11.5	24.7		80.5	30.7	8.0	61.3	100.0		
7032.25	347020.56	4064.99	15101		34.7	0.4	1.5		1.0	25.0	6.3	28.4	60.7		86.8	70.0	1.2	28.8	100.0		
7032.5	330717	14820.35	21375.23		33.1	1.5	2.1		3.7	35.4	8.9	24.1	51.6		90.8	56.9	4.1	39.0	100.0		
7032.75	403104.63	10005.75	20583.69		40.3	1.0	2.1		2.5	34.1	8.6	31.7	67.8		104.5	64.9	2.4	32.7	100.0		
7033	119942.35	1127.5	17794.44		12.0	0.1	1.8		0.3	29.5	7.4	4.5	9.7		39.5	24.6	0.7	74.7	100.0		
	222942.56	4299.89	29898.18		22.3	0.4	3.0		1.1	49.6	12.5	9.8	20.9		71.6	29.2	1.5	69.3	100.0		
	376158.97	6213.1	24693.86		37.6	0.6	2.5		1.6	40.9	10.3	27.3	58.4		100.9	57.9	1.5	40.6	100.0		_
	251071.89	4951.6	30921.59		25.1	0.5	3.1		1.2	51.3	12.9	12.2	26.0		78.5	33.1	1.6	65.3	100.0		
7034			12864.56		36.3	12.2	1.3		30.4	21.3	5.4	30.9	66.1		117.9	56.1	25.8	18.1	100.0		▙
	302233.06	11105.9	32108.84		30.2	1.1	3.2		2.8	53.2	13.4	16.8	35.9		91.9	39.1	3.0	57.9	100.0		
7034.5		3542.73	18464.01		42.8	0.4	1.8		0.9	30.6	7.7	35.1	75.1		106.6	70.4	0.8	28.7	100.0		
	318148.13	7038.07	31359.53		31.8	0.7	3.1		1.8	52.0	13.1	18.7	40.0		93.7	42.7	1.9	55.5	100.0		Н
	298222.38	6246.34	31630.48		29.8	0.6	3.2		1.6	52.4	13.2	16.6	35.5		89.5	39.7	1.7	58.6	100.0		
	356517.25 18790.45	11521.53	32296.79		35.7 1.9	1.2	3.2		0.4	53.5	13.5	22.1	47.4		103.8	45.6	2.8	51.6	100.0		Н
7035.416667 7035.583333		1716.69 3819.36	12714.41 23022.99		34.9	0.2	1.3 2.3		1.0	21.1	5.3	-3.4 25.2	-7.4 54.0		14.1 93.1	-52.1 58.0	3.0 1.0	149.1 41.0	100.0		
7035.833333		761.75	10200.91		18.9	0.4	1.0		0.2	38.2 16.9	9.6 4.3	14.6	31.3		48.4	64.6	0.4	35.0	100.0		
7036.083333		1389.26	12929.38		25.1	0.1	1.3		0.3	21.4	5.4	19.7	42.2		64.0	66.0	0.4	33.5	100.0		
7036.333333		8657.8	22429.59		34.5	0.9	2.2		2.2	37.2	9.4	25.1	53.7		93.0	57.7	2.3	40.0	100.0		
7036.583333		6537.06	14352.02		42.4	0.7	1.4		1.6	23.8	6.0	36.4	77.9		103.3	75.4	1.6	23.0	100.0		
7037.833333		20918.96	21749.88		32.0	2.1	2.2		5.2	36.1	9.1	22.9	48.9		90.2	54.2	5.8	40.0	100.0		
7038.083333			23653.74		34.9	1.4	2.4		3.5	39.2	9.9	25.0	53.4		96.1	55.6	3.6	40.8	100.0		
7038.333333		10618.21	27188.69		28.3	1.1	2.7		2.7	45.1	11.4	17.0	36.3		84.0	43.2	3.2	53.6	100.0		
7038.583333		2925.22	17794.21		18.3	0.3	1.8		0.7	29.5	7.4	10.8	23.2		53.4	43.4	1.4	55.3	100.0		
	338353.34	59345.7	24051.04		33.8	5.9	2.4		14.8	39.9	10.1	23.8	50.9		105.6	48.2	14.1	37.8	100.0		
4 and 5 missing	XF	F Elemental D	ata													XRF Model (Qua	artz, Calcite and I	llite)			

- 1) Ca is 40% of CaCO3 (calcite), consequently %calcite = 2.5Ca (where no other Ca-carbonate phases are present)
- 2) K averages 6% of illite (Weaver, 1965), consequently %illite = 16.58 K
- 3) Si averages 25% of illite (Mermut and Cano, 2001), which has to be subtracted from total Si before % quartz is calculated, consequently Si_{illite} = %illite × 0.25
- **4)** Si is 47% of SiO2 (quartz), consequently %quartz = (%Si_{total} %Si_{illite}) × 2.14
- **5)** Final mineral values are normalized, so that calcite + quartz + illite = 100%.

Mineral Model: Koch

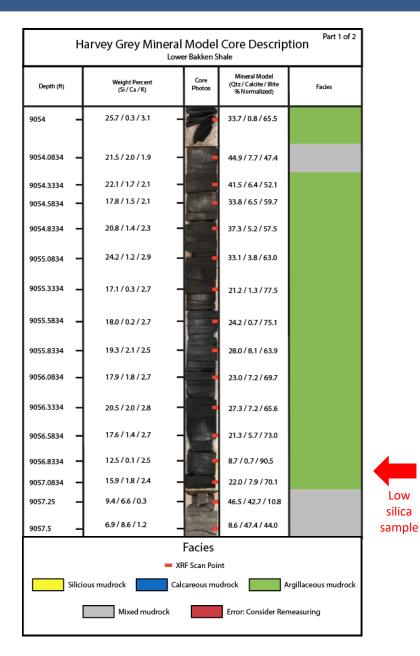


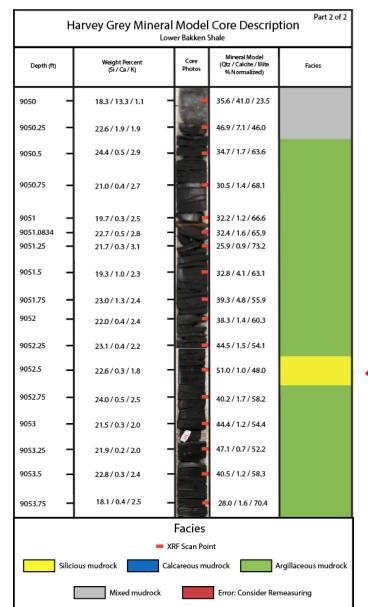




Mineral Model: Harvey Grey



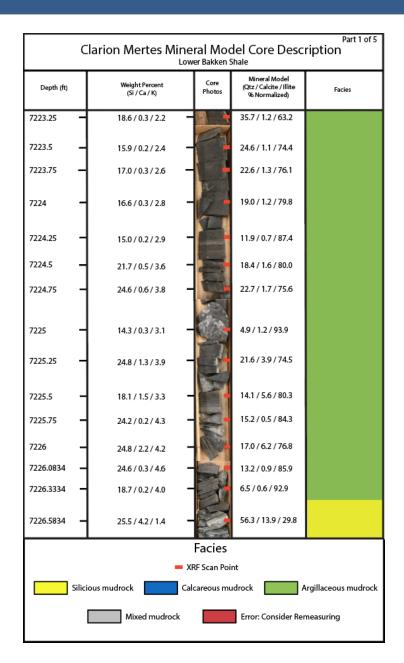


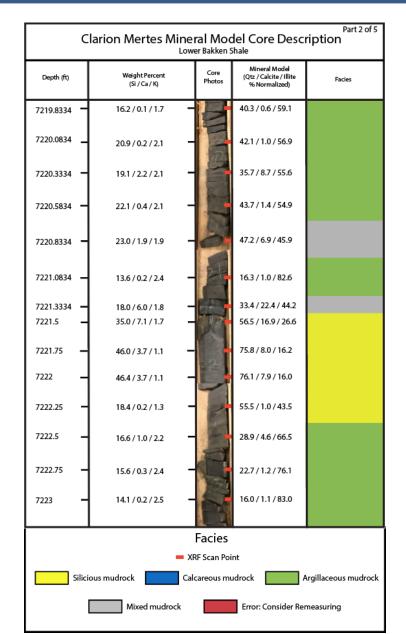


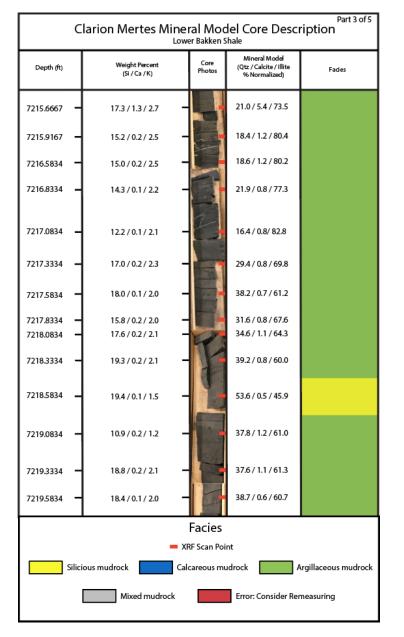


Mineral Model: Clarion Mertes Part 1



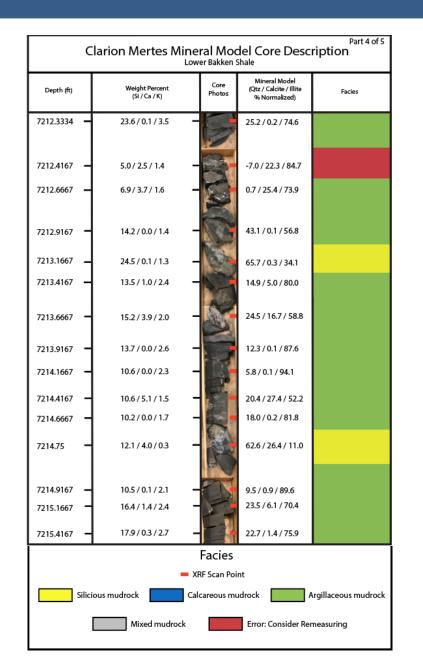


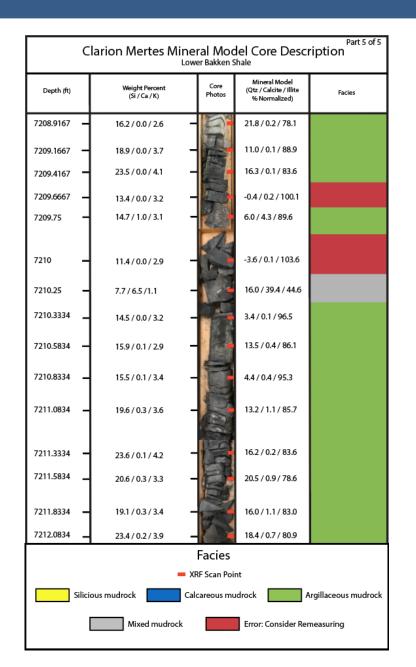




Mineral Model: Clarion Mertes Part 2



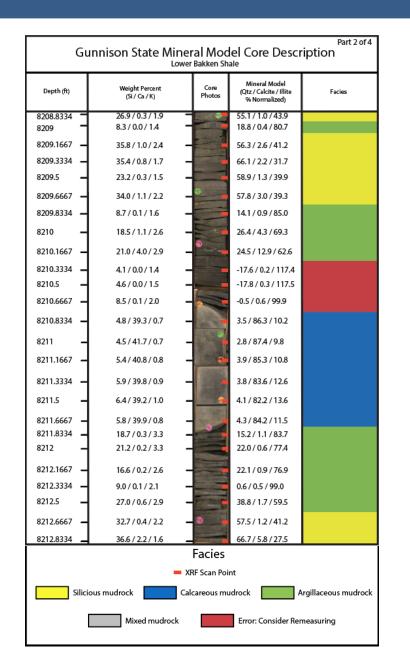




Mineral Model: Gunnison State Part 1

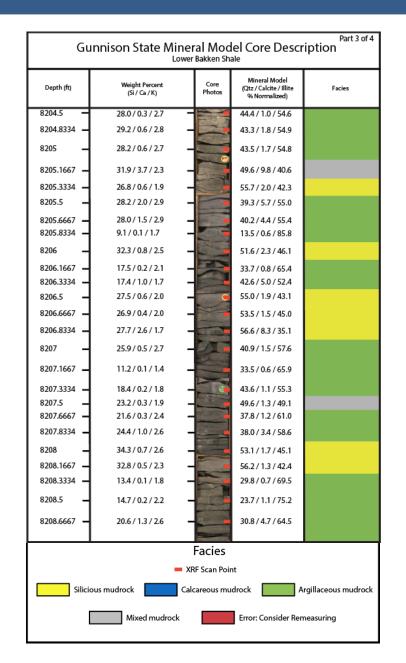


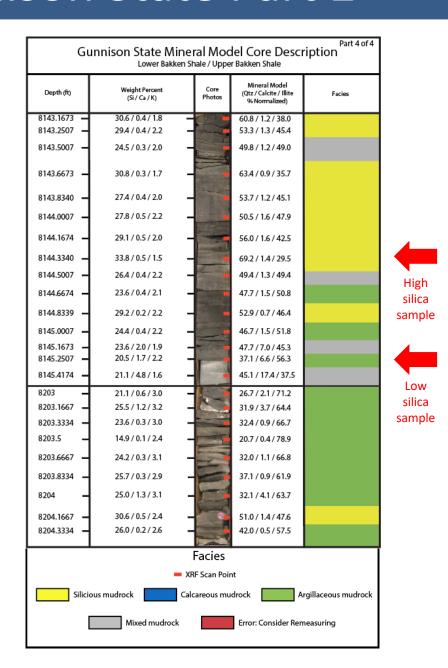
Depth (ft)	Weight Percent (Si / Ca / K)	Core Photos	Mineral Model (Qtz / Calcite / Illite % Normalized)	Facies
8213 —	19.9 / 2.6 / 1.8		42.5 / 10.4 / 47.1	
8213.1667 —	28.1 / 0.5 / 3.0		39.3 / 1.5 / 59.2	
8213.3334 -	13.6 / 0.1 / 1.7		34.0 / 0.6 / 65.4	
8213.5	20.2 / 0.2 / 1.7		49.5 / 0.9 / 49.6	
8213.6667 —	34.5 / 1.1 / 1.9		62.9 / 3.0 / 34.1	
8213.8334 -	28.2 / 0.6 / 3.0	-	40.0 / 1.7 / 58.3	
8214 -	24.7 / 0.3 / 3.2	- 3	31.5 / 0.9 / 67.7	
8214.1667 —	18.8 / 0.3 / 2.2		35.4 / 1.1 / 63.5	
8214.3334 -	25.3 / 0.6 / 2.6		41.0 / 2.1 / 56.9	
8214.4167 — 8214.5 —	20.3 / 0.7 / 2.9 28.1 / 0.4 / 2.9	-	26.5 / 2.7 / 70.9 41.0 / 1.2 / 57.8	
8214.6667 -	27.1/0.3/3.2		35.2 / 1.0 / 63.8	
8214.8334 —	27.4/0.3/3.1		36.7 / 1.0 / 62.3	
8215 -	21.7 / 0.2 / 2.8	nl 👅	30.5 / 0.6 / 68.9	
8215.0834 -	4.7 / 0.0 / 1.5	- 14 (-13.6 / 0.2 / 113.4	
8215.25	11.9 / 0.1 / 2.4		9.3 / 0.5 / 90.2	
8215.3334 -	25.8 / 0.4 / 3.3		31.7 / 1.2 / 67.1	
8215.5	22.9 / 0.2 / 3.1	_	29.0 / 0.7 / 70.3	
8215.6667 -	25.7 / 0.4 / 3.4		29.6 / 1.2 / 69.1	
8215.8334 -	24.9 / 0.3 / 3.4		28.2 / 1.1 / 70.7	
8216 _	25.8 / 0.4 / 3.4	5 -	29.8 / 1.2 / 69.0	
8216.25	20.9 / 0.3 / 3.5		19.1 / 0.9 / 80.0	
8216.5	31.3 / 0.7 / 4.6		25.1 / 1.6 / 73.3	
8216.5834 -	15.3 / 0.0 / 3.4	2005	4.0 / 0.2 / 95.8	
8216.8334 -	7.8 / 0.0 / 2.5		-16.3 / 0.1 / 116.2	
8217.0834 -	5.2 / 0.0 / 1.9		-22.1 / 0.3 / 121.8	
8217.3334 -	11.7 / 4.3 / 2.0	19 (8)	14.7 / 21.3 / 64.0	
		Facies		
	-)	(RF Scan Poi	nt	
Silici	ous mudrock Ca	alcareous mu	ıdrock A	rgillaceous mudroc



Mineral Model: Gunnison State Part 2







Outline



• Bakken Formation / Silica Diagenesis Introduction

Core Overview

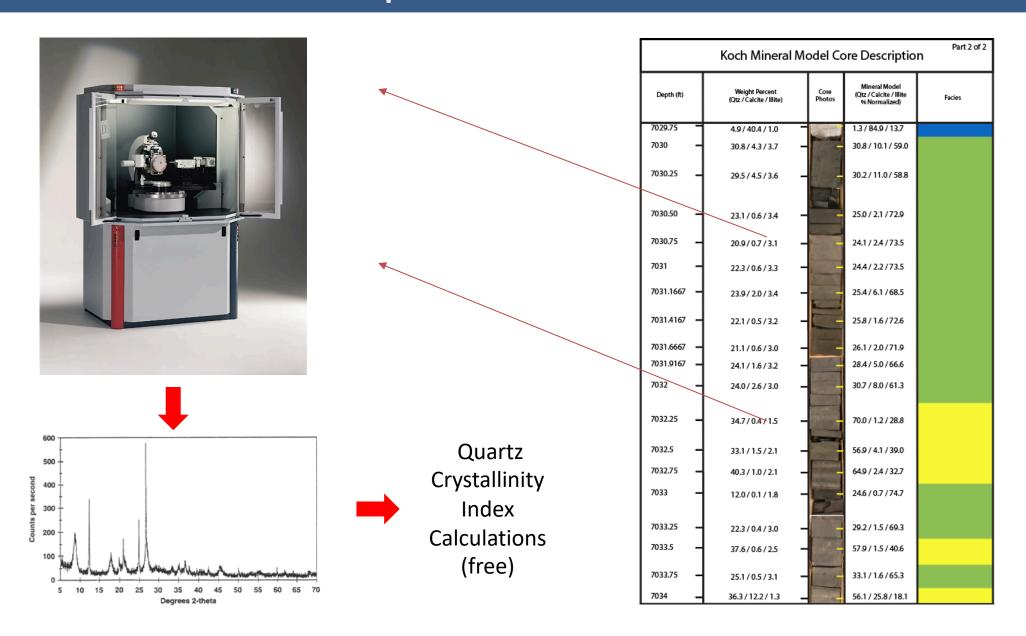
XRF Data

Mineral Model Core Descriptions

Next Steps

Next Steps: XRD Measurements

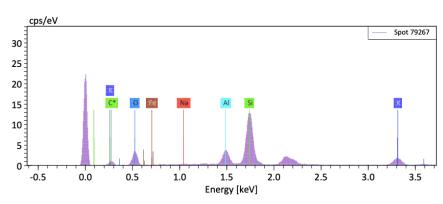


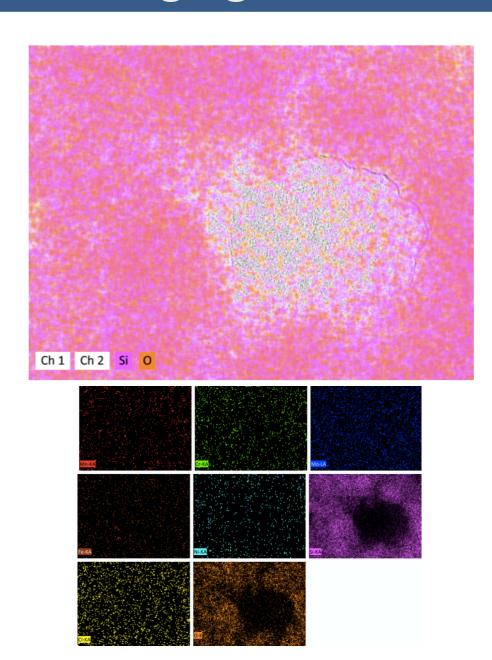


Next Steps: FESEM Imaging









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