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UNIVERSITY OF WYOMING

Sealing Capacity Investigations of the Multiple Confining Layers at the RSU Geological CO_2 Storage Site

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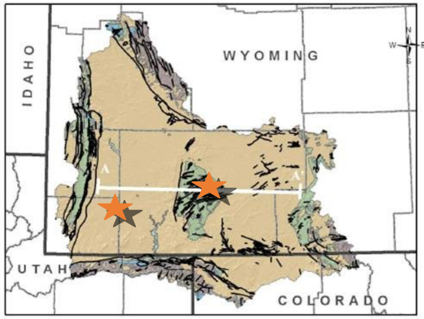
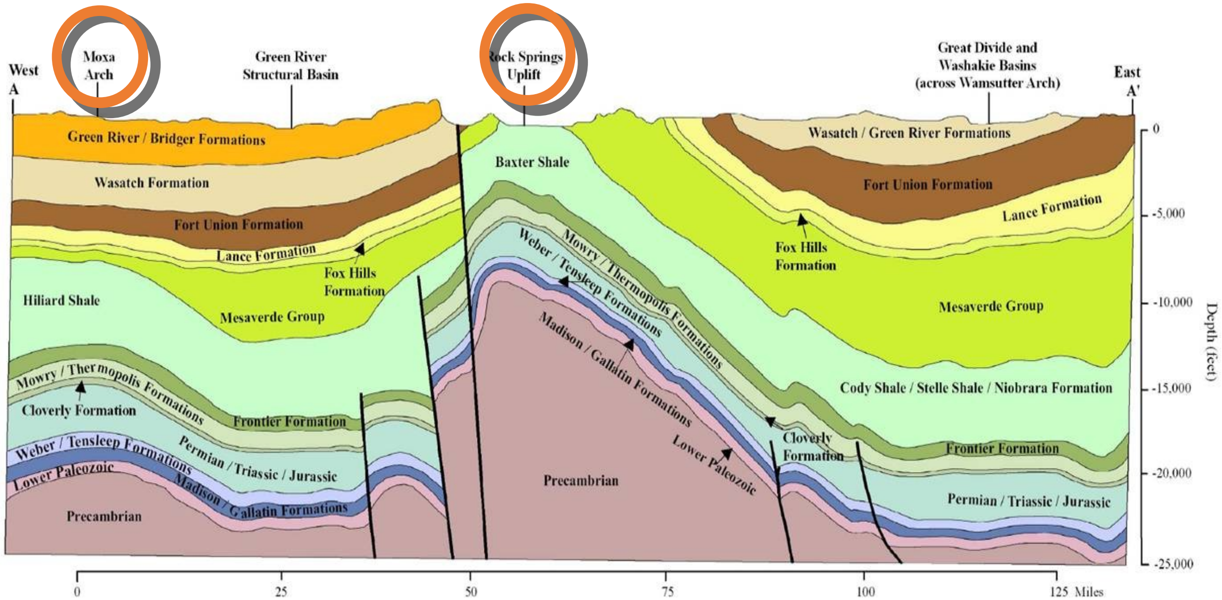
Outline

1. The Rock Springs Uplift (RSU) geological CO_2 storage site characterization
2. The CO_2 storage capacity and CO_2 column high assessment of the RSU storage site
3. Petrophysical and petrographic characteristics of confining layers at the RSU site
4. Determination of the sealing capacities of the confining layers in a CO_2-brine-rock system
5. Remarks

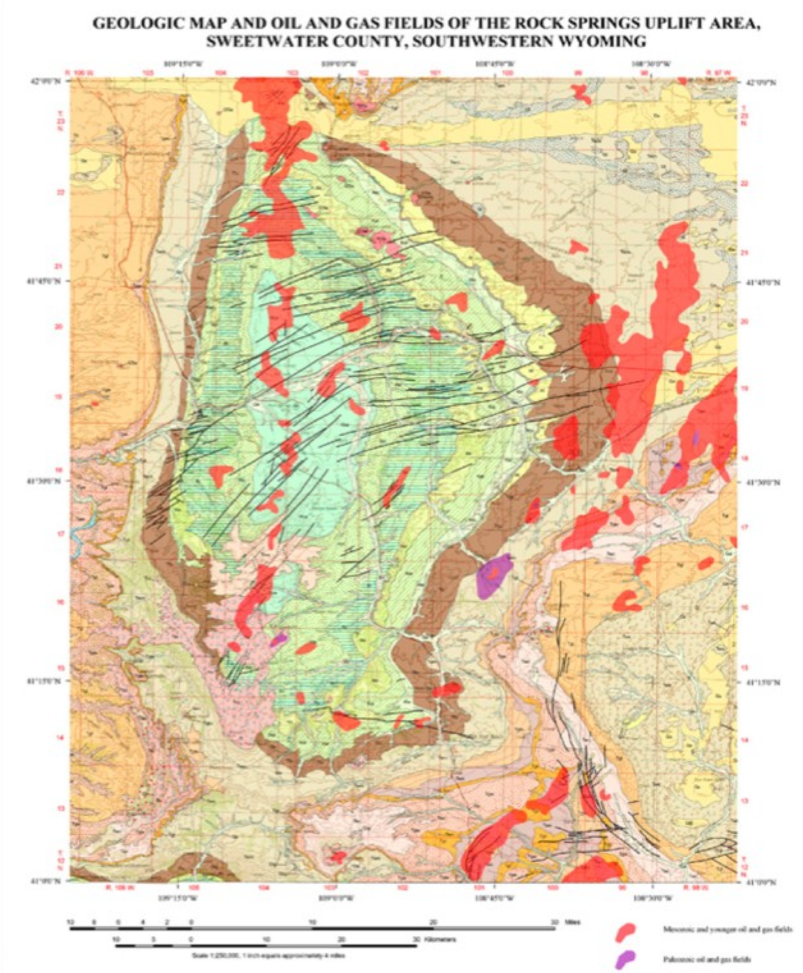
Priority Carbon Storage Sites in SW Wyoming



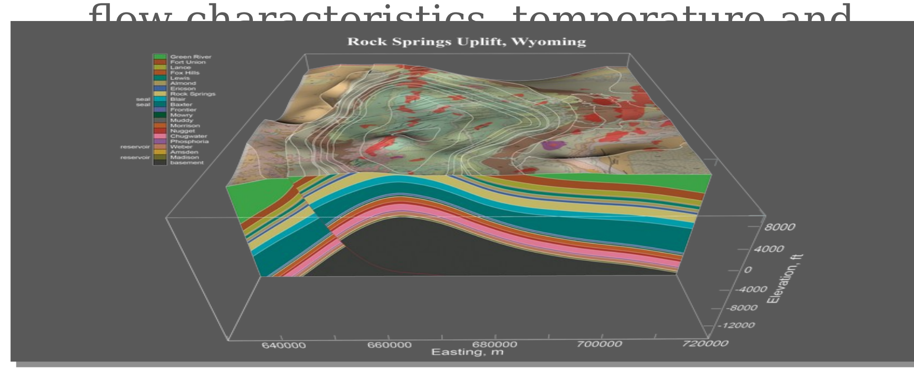
WSGS, UW, WY, and DOE-funded research identified two high-potential CCUS sites in southwest Wyoming: *Rock Springs Uplift* and *Moxa Arch*



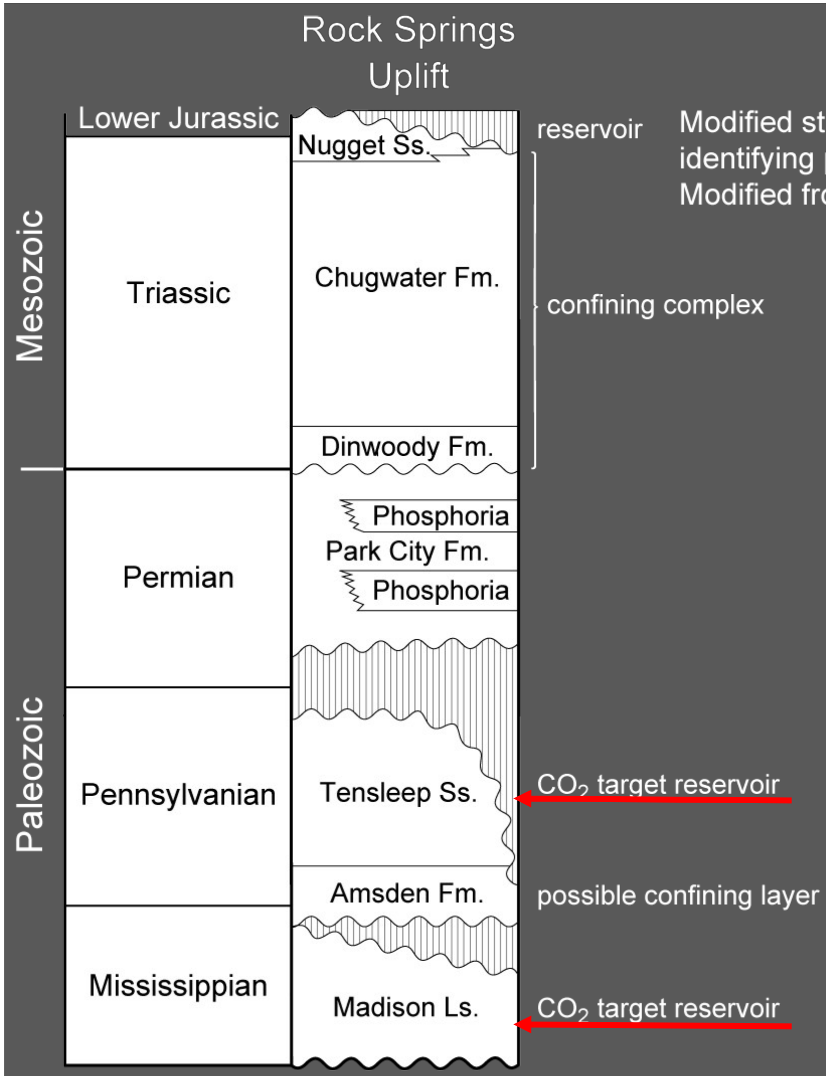
The Rock Springs Uplift: an Outstanding Geological CO_2 Storage Site in SW Wyoming



- Multiple thick saline aquifer sequences overlain by thick sealing lithologies (8000 feet of vertical separation between CO_2 storage reservoirs and fresh water aquifers)
- Doubly-plunging anticline characterized by more than 10,000 feet of closed structural relief
- Huge area (50 x 35 miles)
- Required reservoir conditions, including, but not limited to fluid chemistry, porosity (pore space), fluid-flow characteristics, temperature and

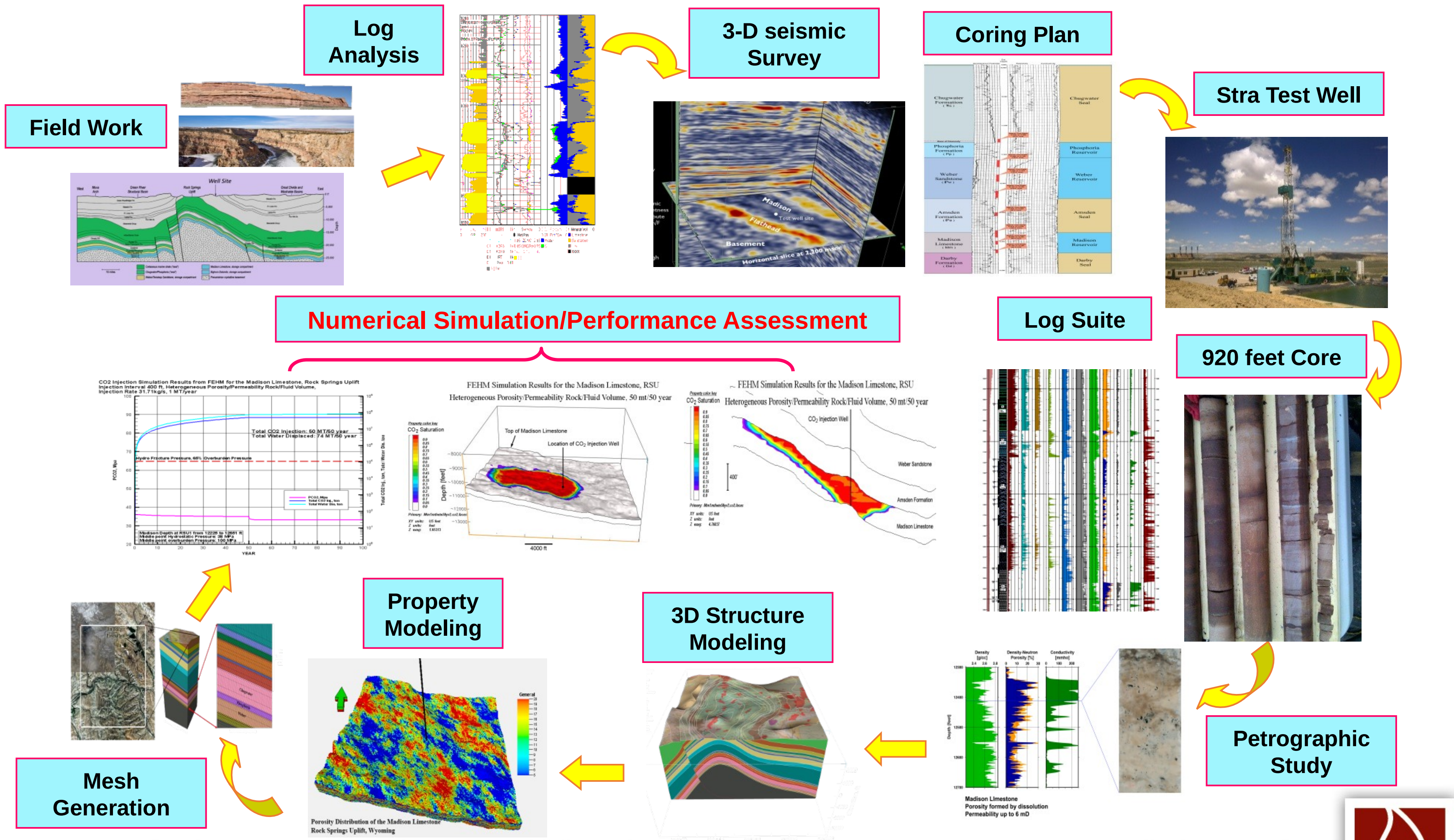


Targeted Geological CO_2 Storage Saline Formations



Modified stratigraphic column of the Rock Springs Uplift identifying possible confining layers and CO_2 target reservoirs. Modified from Love, Christiansen, and VerPloeg, 1993.

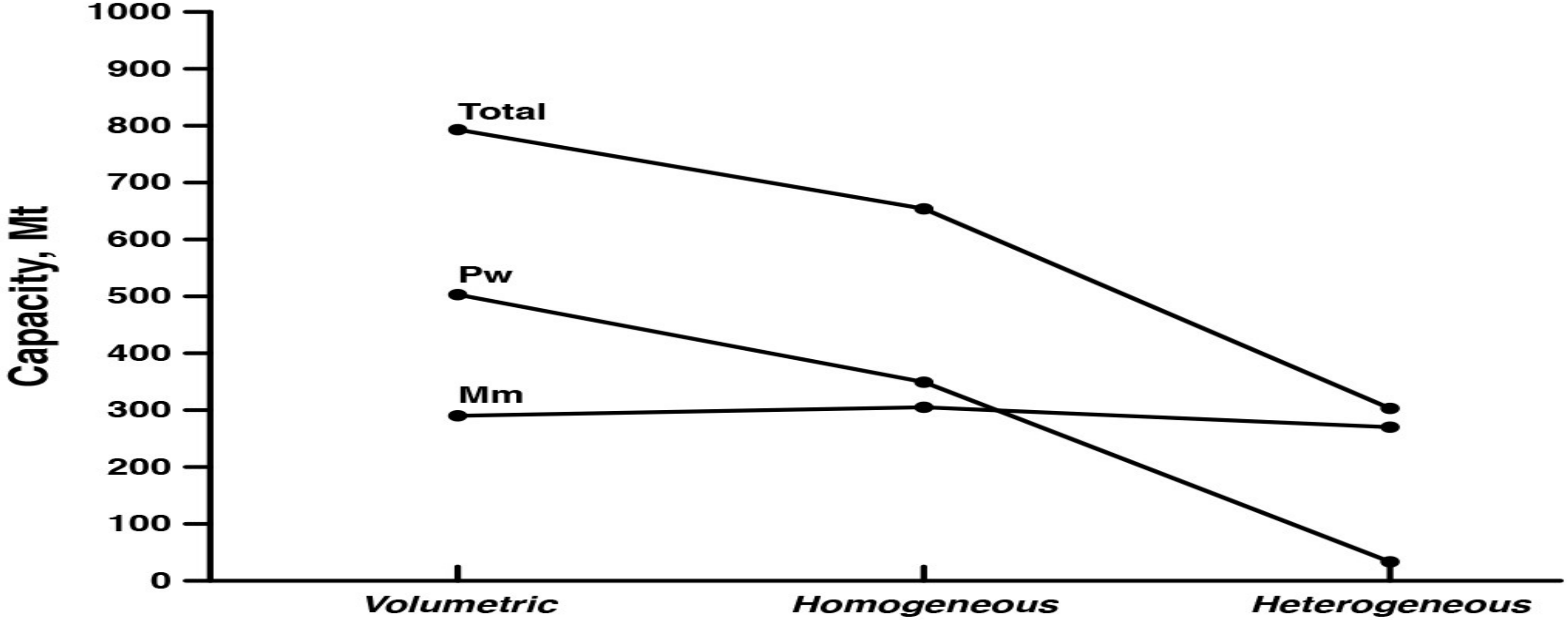
Work Flow for Geological CO_2 Storage Site Characterization



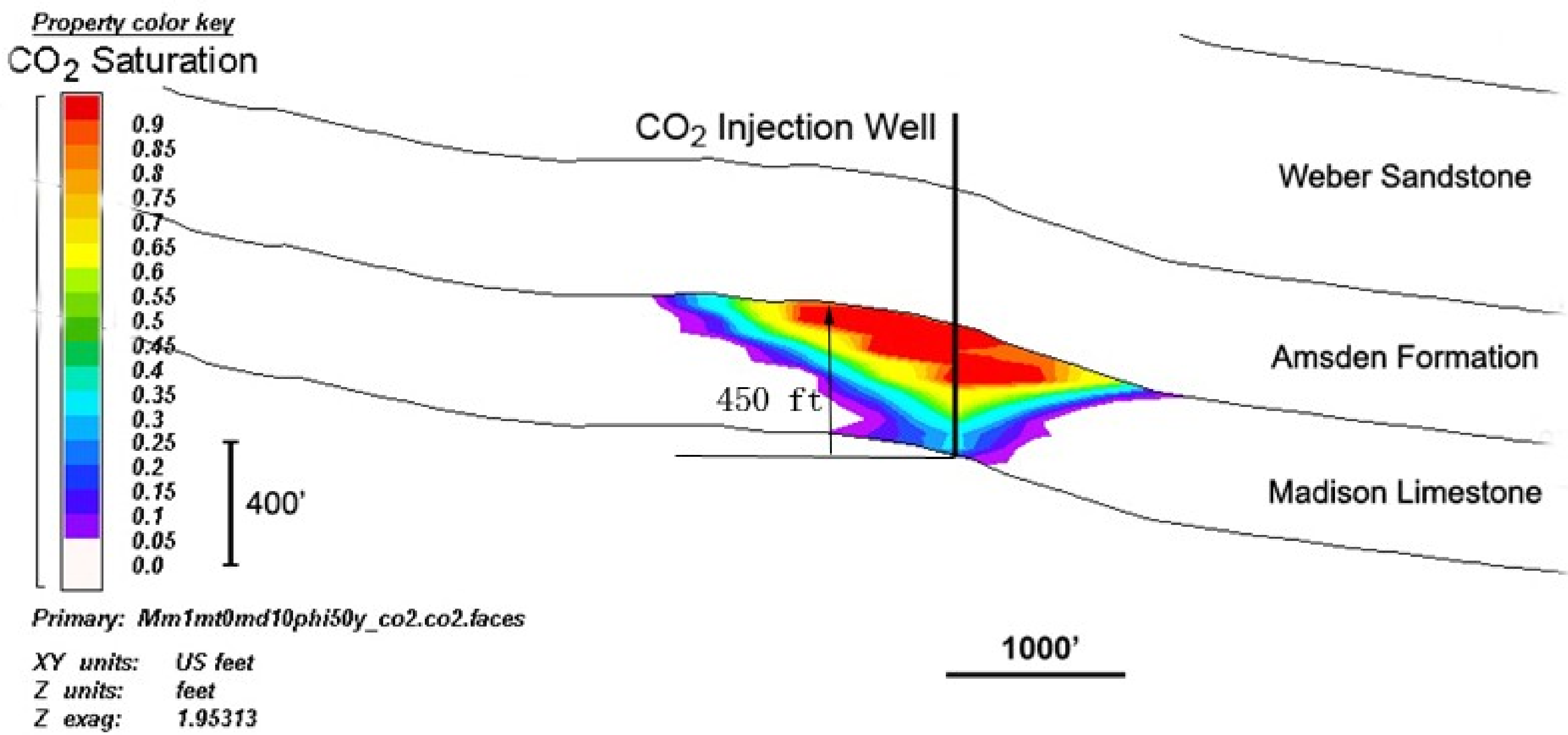
Comparison of CO_2 Storage Capacity Utilizing 3 Different Techniques – 5 mi x 5 mi storage domain

			Static Volumetric Approach[1]	*Dynamic Numerical Simulation*[2] *Homogenous Reservoir Model*			*Dynamic Numerical Simulation*[2] *Heterogeneous Reservoir Model*		
Formation	**Area, km^2**	**Thickness, m**	**Storage Capacity, Mt**	**Injection Rate, Mt/y**	**Storage Capacity, Mt**	**Injection Wells**	**Injection Rate, Mt/y**	**Storage Capacity, Mt**	**Injection Wells**
Weber	64	210	503	1.0	350	7	0.3	33	7
Madison	64	120	290	1.0	305	6	1.0	270	6

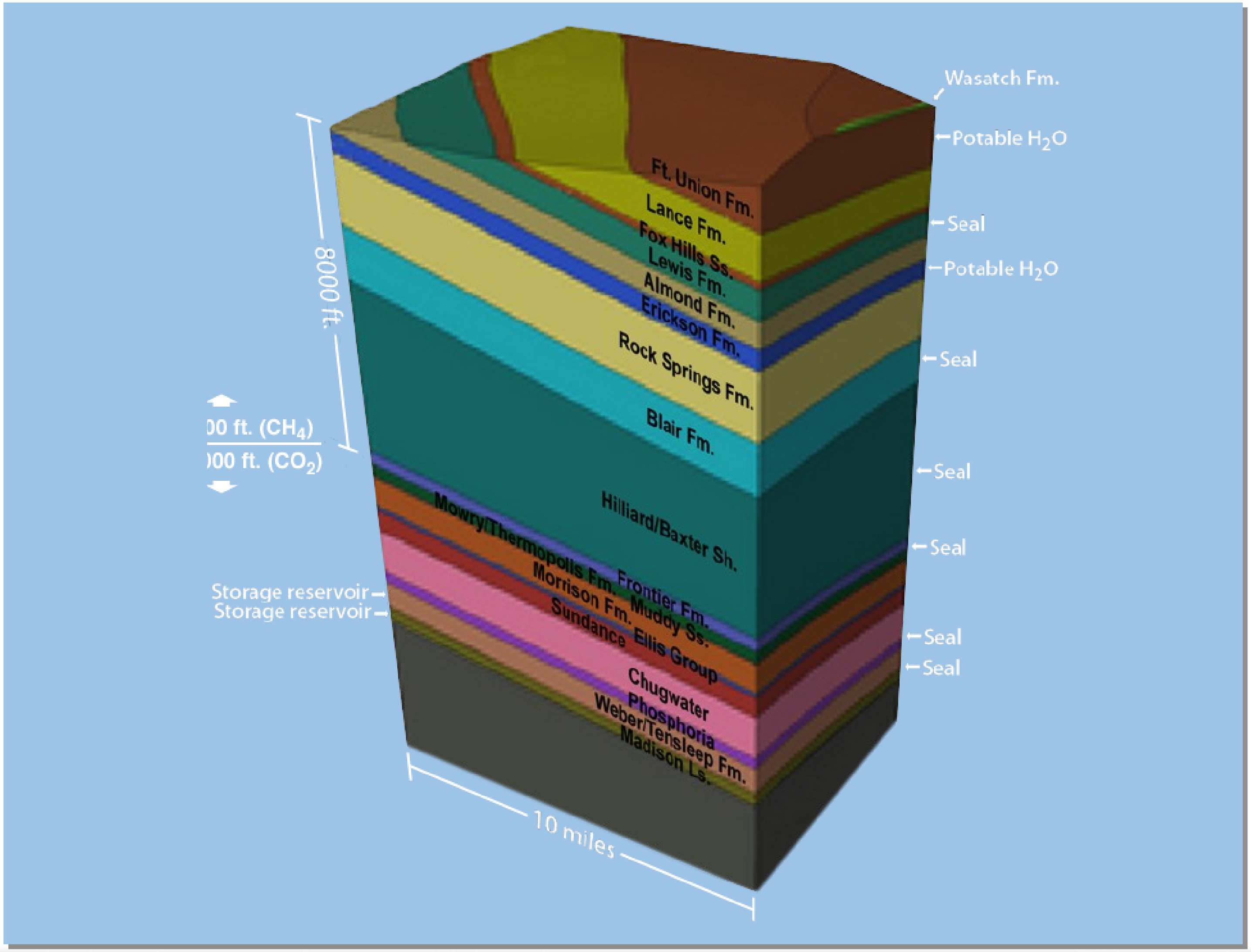
1 – USGS Open File Report 2009-1035
2 – FEHM, Los Alomos National Laboratory



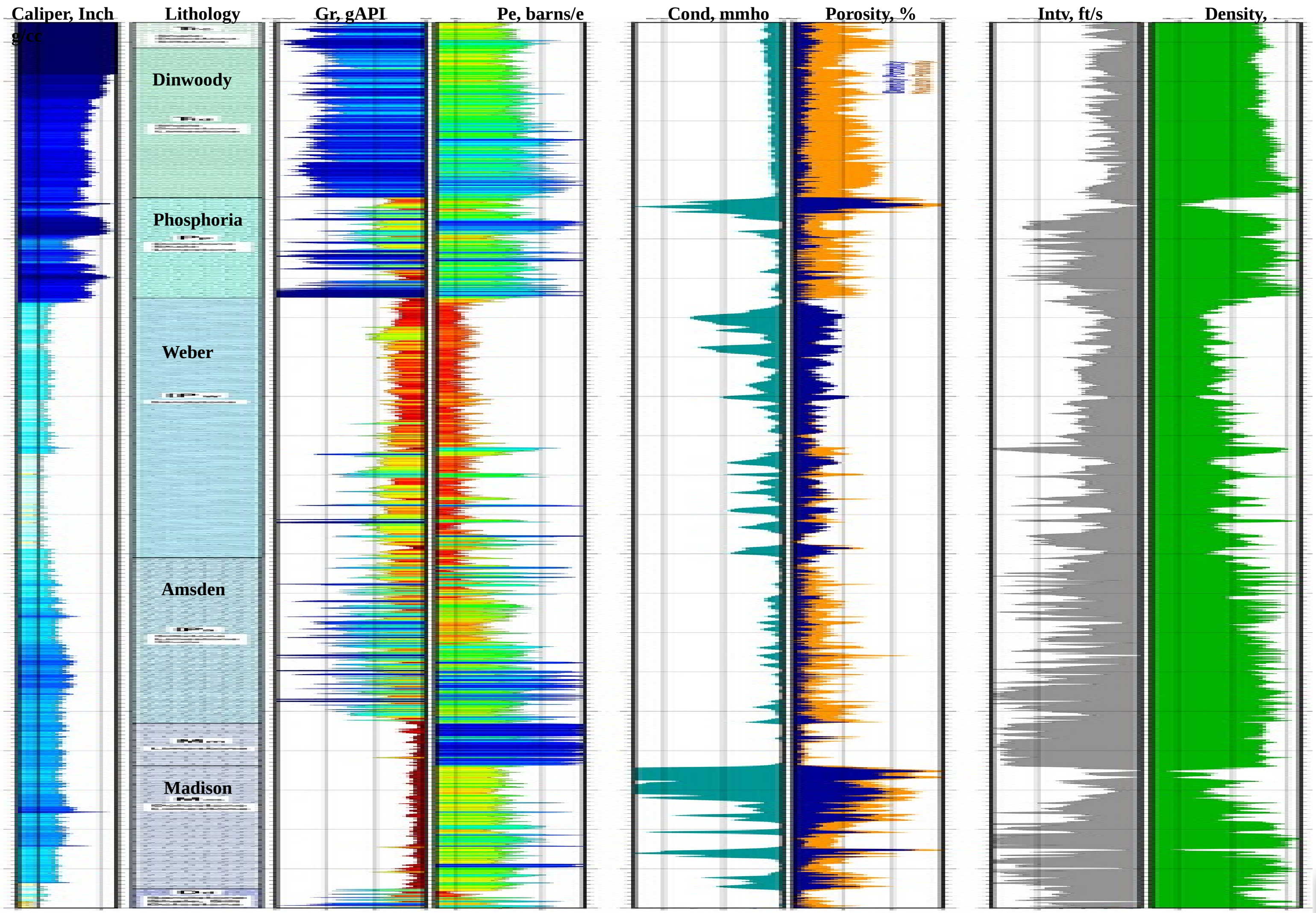
FEHM Simulation Results for the Madison Limestone, RSU
Homogeneous Porosity/Permeability Rock/Fluid Volume
Porosity 10%, Permeability 10 md, 50 Mt/50 years



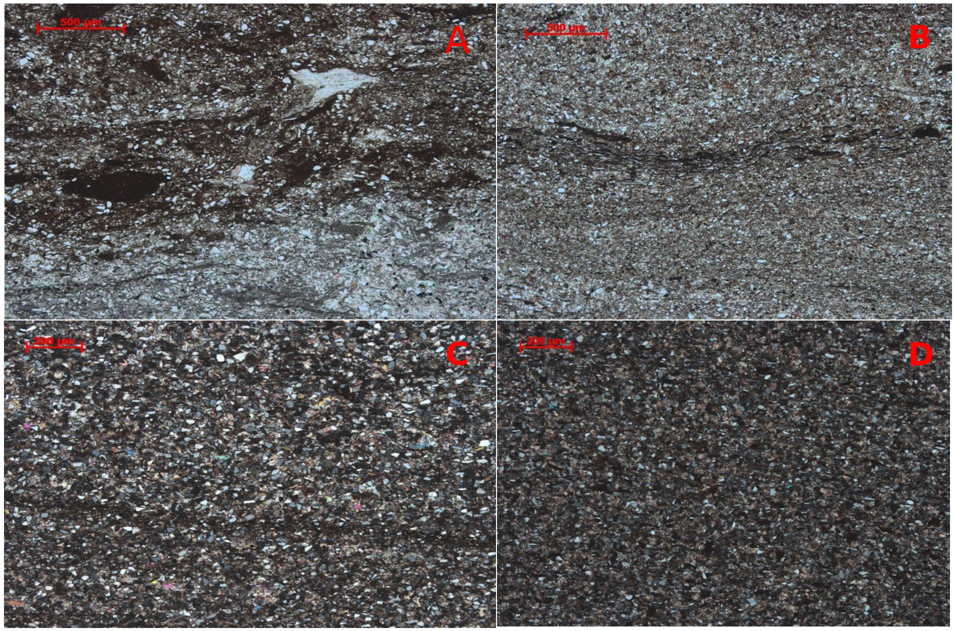
Rock Springs Uplift Hydrostratigraphic System



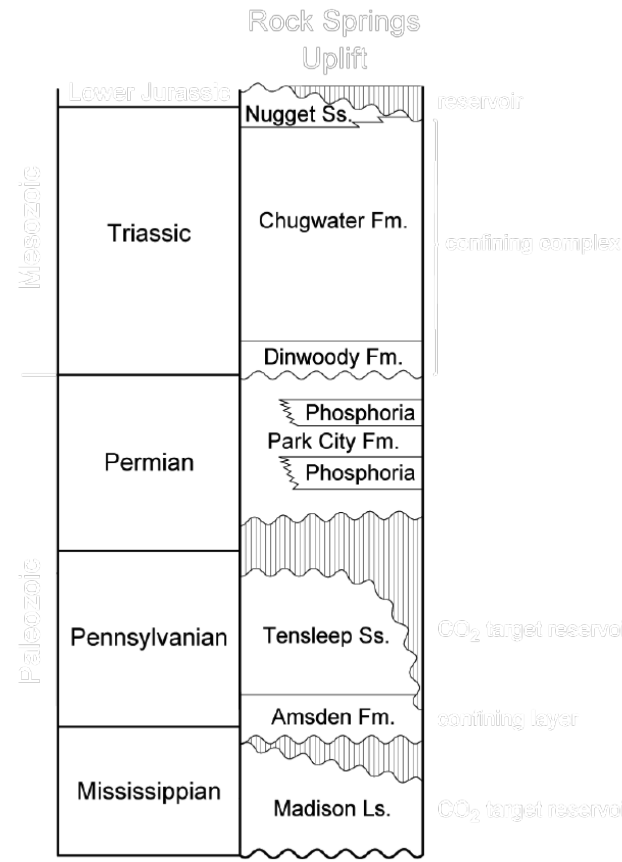
Stratigraphic Column and Select Petrophysical Logs for RSU #1



Chugwater Group (Primary Seal for the Weber Sandstone



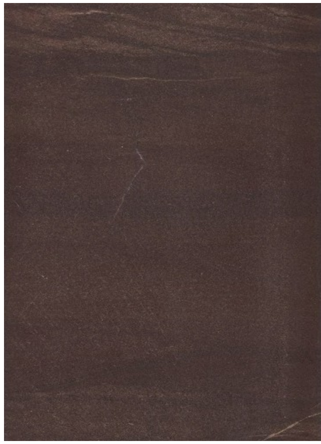
Microphotographs of Chugwater Group siltstones at depths of A: 10,627.8’, B: 10,662.8’, C: 10,682.1’ and D: 10,601.9’ clockwise from top left. C and D represent typical, laminated siltstones of the Chugwater Group. Petrographic porosity is negligible due to cementation. A: shows mud intraclasts, anhydrite nodules, and a contact at a reduction zone (bottom part of slide, light-colored). Calcite increases in the reduction zones as it replaces anhydrite. B: shows increased illite compositions along a minor mineralization band.



Modified stratigraphic column of the Rock Springs Uplift identifying confining layers and CO_2 target reservoirs. Modified from Love, Christiansen, and VerPloeg, 1993.

Porosity (Hg) = 3%
Permeability = 0.003 md

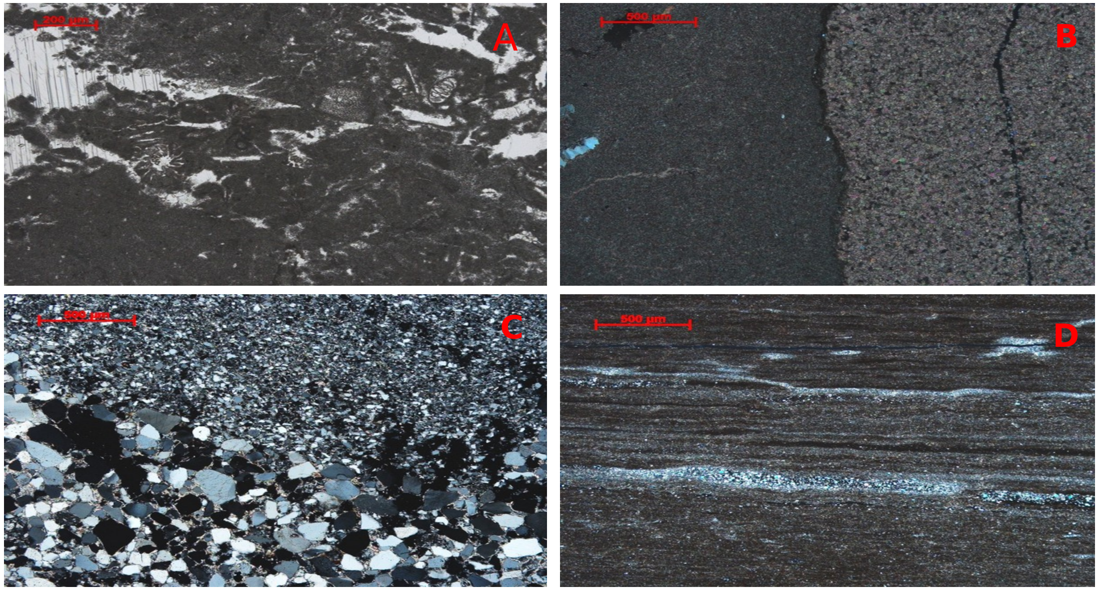
Chugwater Group Siltstones

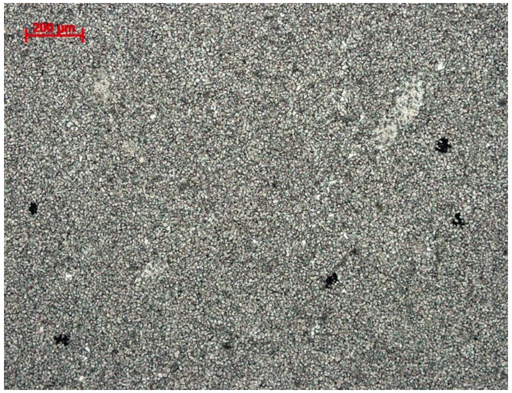


Porosity (Hg) = 2%
Permeability = 0.005 md

Porosity (Hg) = 2%
Permeability = 0.003 md

Amsden Formation (Primary Seal for the Madison limestone)



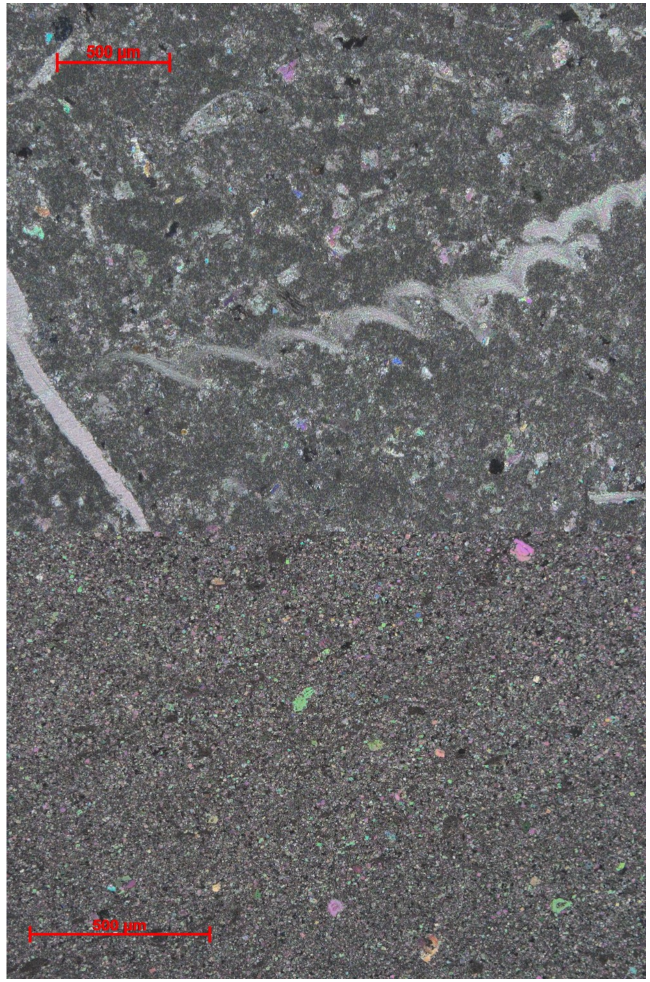


Porosity (Hg), 2%
Permeability, 0.003 md

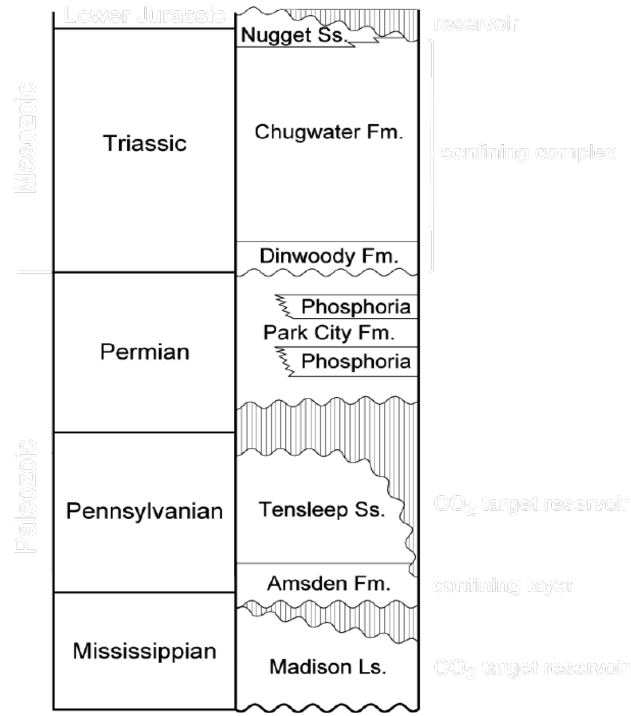
Microphotographs of the Amsden Formation at depths of A: 12,203’, B: 12,218.7’, C: 12,199’, and D: 12,209’ clockwise from top left. Note the heterogeneity in lithologies from the fossiliferous limestone in A to the fine-grained siltstone in C to the bimodal sandstone in D, All slides have some evidence of secondary mineralization and deep burial alteration, figures succinctly displays a contact between neomorphic calcite (right portion of slide, reddish) and the primary micritic limestone with chert cements. A thin, dark dissolution band of insoluble minerals separates the facies.

The Most Up-Portion of the Madison Limestone (Primary Seal)

12,250.0 ft.



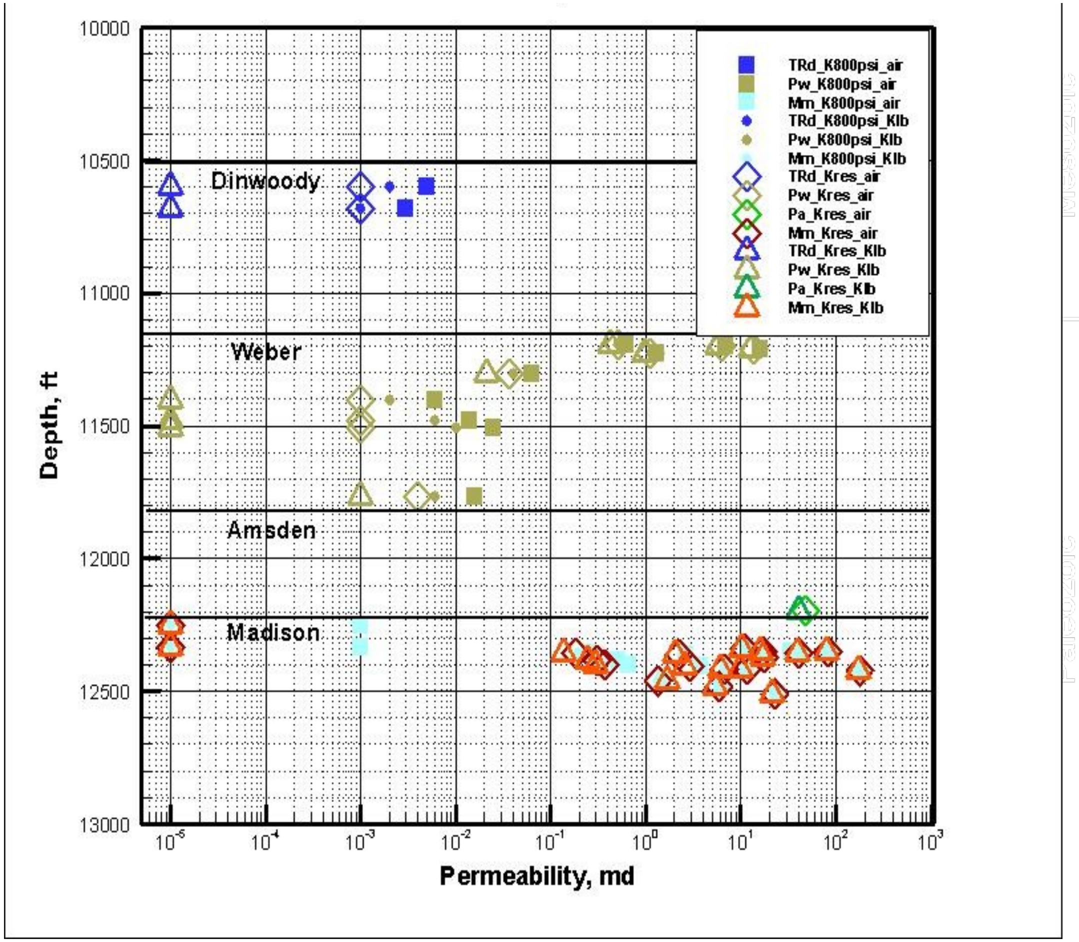
Typical fossiliferous micrites in the Madison limestone facies and depths of A: 12,249.8’ and B: 12,233’. This facies is typified by mainly primary features, lack of developed pore space, and micritic cements.

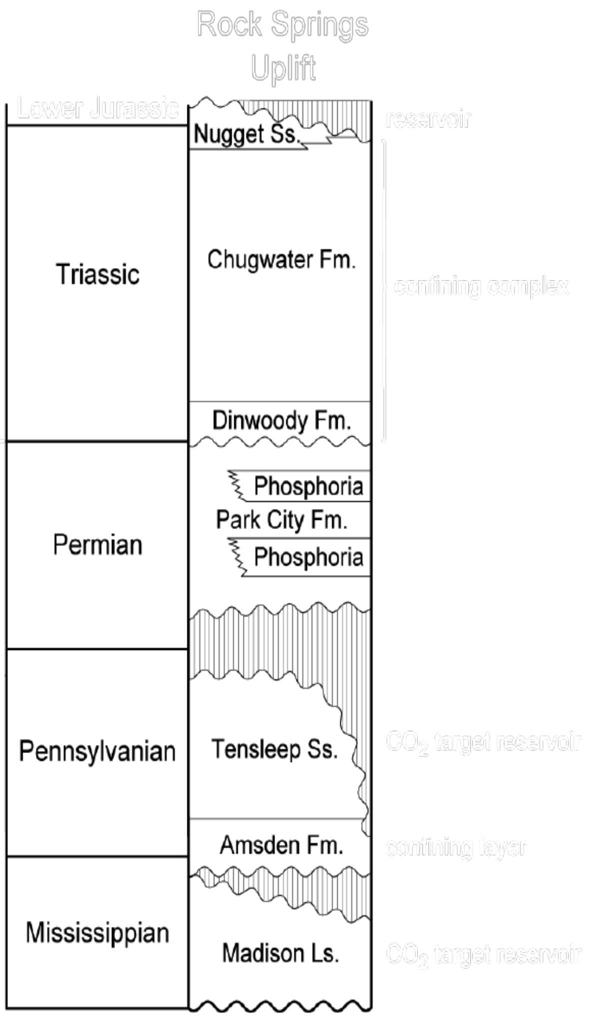


Modified stratigraphic column of the Rock Springs Uplift identifying confining layers and CO_2 target reservoirs. Modified from Love, Christiansen, and VerPloeg, 1993.

Porosity (Hg) = 1.9%
Permeability = 0.001 md

The Air and Klinkenberg Permeabilities of Core from RSU #1





Modified stratigraphic column of the Rock Springs Uplift identifying confining layers and CO_2 target reservoirs. Modified from Love, Christiansen, and VerPloeg, 1993.

Entry Pressures and Column High

The subsurface hydrocarbon-water or CO_2-water entry pressure values can be derived from the mercury entry pressure values by using following equation (Purcell, 1949, Schowalter, 1979):

$$Pc\_res = \mathrm{Pc}\_ma * \frac{\gamma res * \cos\theta res}{\gamma ma * cos\theta ma}$$

The height of a hydrocarbon or supercritical CO2 column that a confining layer can hold, can be determined by using following equation (Smith, 1966, Schowalter, 1979):

$$H = \frac{Pds - Pdr}{(\rho w - \rho co2) * 0.433}$$

Parameters Used for the Displacement Pressure Calculations

Parameters used for Displacement Pressure Calculation					
Laboratry IFT					
Air/mercury IFT =	485		Height above free water		
Gas/water IFT =	72				
Gas/Oil IFT =	24			g/cm3	psi/ft
Oil/Water IFT =	48		density brine =	1.080	0.468
			density of oil =	0.840	0.364
Reservoir IFT			density of gas =	0.200	0.087
Gas/water IFT =	50				
Oil/Water IFT =	30				
CO2/Water IFT =	30		gas/water coef =	2.62	
			oil/water coef. =	9.62	
Laboratory Contact Angle		Cosine Contact Angle			
Air/Water	0	1.000			
Oil-Water	30	0.866			
Air-Mercury against rock	140	0.766			
Air-Oil	0	1.000			
Reservoir Contact Angle					
Water/Gas contact angle	0	1.000			
Water/Oil contact angle	30	0.866			
CO2/Water contact angle	60	0.500			
Laboratory IFT*Cosine Contact Angle					
Air/Water		72			
Oil-Water		42			
Air-Oil		24			
Air/Mercury		372			
Reservoir IFT*Cosine Contact Angle					
Air/Water		50			
Oil-Water		26			
CO2-water		15			

Intertek, 2014, Chun and Wilkinson (1995), Yang et al. (2005), Dickson et al. (2006), Chalbaud et al. (2006, 2009), Chiquet et al. (2007), Espinoza and Santamarina (2010), Wollenweber et al. (2010), Daniel et al., (2009), Buursink et al. (2011), silva et al. (2012), and Edlmann et al. (2013).

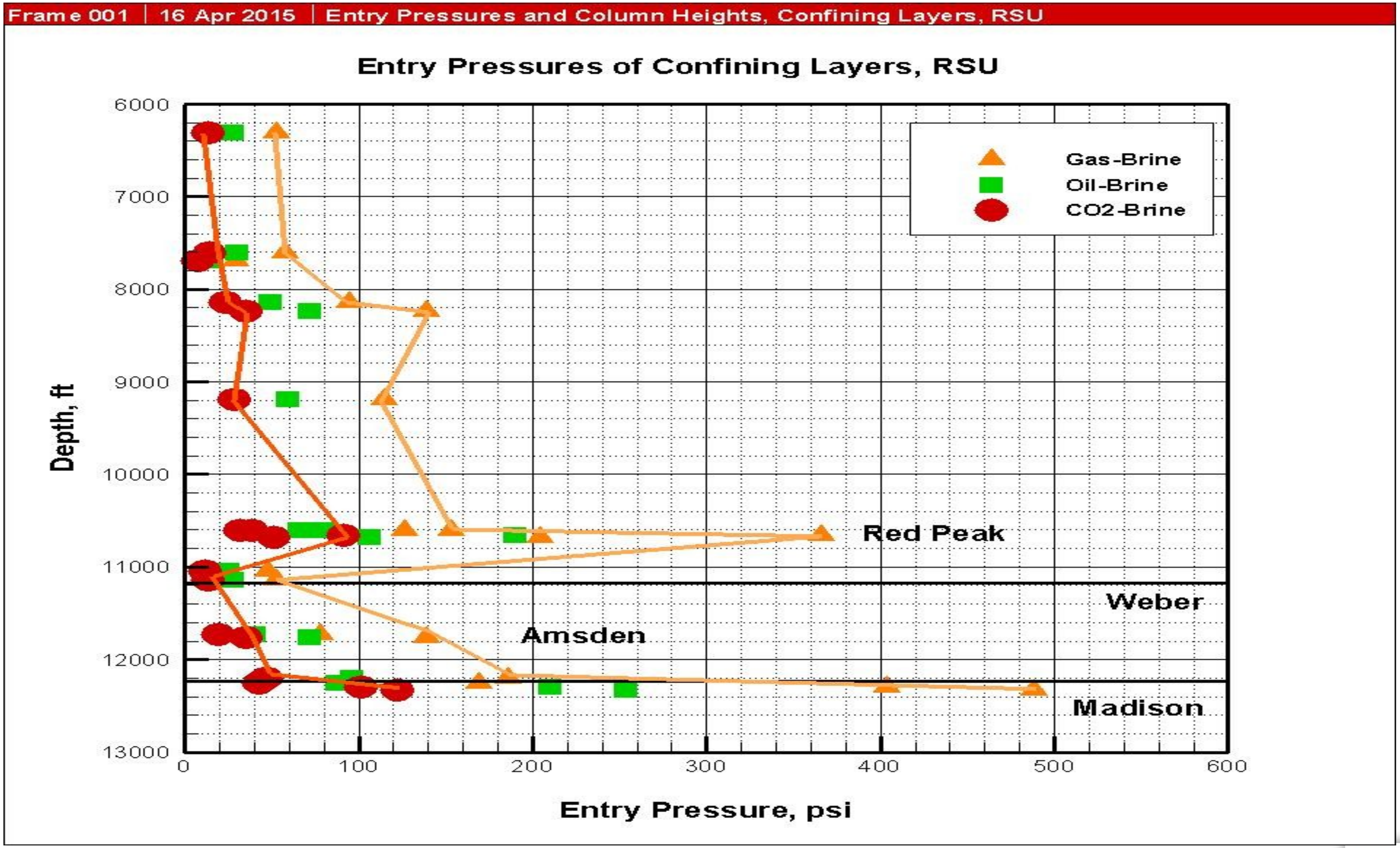
Entry Pressures Derived from High-Pressure Mercury Injection Test Results (Lab Condition)

Sample ID	Interral Depth ft	Formation ID	Sample Type	Grain Density g/cc	Porosity Helium %	Entry Pressure (lab) A-Hg psi	G-W psia	O-W psia
176	11725.9	WebeR 1	CoLe Plug	2.70	0.40	576.5	111.727	64.506
187	12178.1	Amsden 1	Core Plug	2.91	5.89	146.6	28.402	16.398
200	12227.3	Amsden 2	Core Plug	2.85	2.60	80.5	15.605	9.010
206	12301.0	Madison	Core Plug	2.74	1.90	3000.0	581.377	335.658
214	12333.9	Madison 1	Core Plug	2.83		3630.1	703.488	406.159
B1	6300-6330	Baxter 1	Cuttings	2.59		390.4	75.661	43.683
B2	7680-7710	Baxter 2	Cuttings	2.57		217.3	42.102	24.307
B3	7590-7620	Baxter 3	Cuttings	2.49		430.6	83.452	48.181
M1	8130-8160	Mowry 1	Cuttings	2.51		701.0	135.854	78.435
M1	8220-8250	Mowry 2	Cuttings	2.50		1032.4	200.075	115.513
GS1	9190-9200	Gypsum Springs 1	Cuttings	2.59		850.3	164.790	95.142
P1	11040-11050	Phosphoria 1	Cuttings	2.71		354.5	68.696	39.661
P2	11140-11150	Phosphoria 2	Cuttings	2.65		389.7	75.530	43.607
1	10601.9	Red Peak	Core Plug		1.60	939.7	182.107	105.139
4	10605.9	Red Peak	Core Plug		1.60	1140.0	220.923	127.550
16	10656.4	Red Peak	Core Plug		1.00	2719.0	526.922	304.218
18	10682.1	Red Peak	Core Plug		1.20	1521.0	294.758	170.179
26	11209.9	Weber	Core Plug		8.10	7.8	1.512	0.873
27	11227.1	Weber	Core Plug		7.60	35.0	6.783	3.916
45	11766.8	Weber	Core Plug		1.30	1034.0	200.381	115.690
53	12197.4	Amsden	Core Plug		5.80	1381.0	267.627	154.515
59	12250.0	Madison	Core Plug		1.30	1254.0	243.016	140.305
72	12348.9	Madison	Core Plug		18.10	22.0	4.263	2.461
79	12354.7	Madison	Core Plug		23.50	35.0	6.783	3.916
99	12399.0	Madison	Core Plug		11.60	37.0	7.170	4.140
106	12415.1	Madison	Core Plug		18.50	9.1	1.764	1.018
110	12480.5	Madison	Core Plug		11.80	5.1	0.984	0.568

Entry Pressures Derived from High-Pressure Mercury Injection Test Results (Reservoir Condition)

-	Interral		Sample	Grain	Porosity	Entry Pressure (res)			
Sample	Depth	Formation	Type	Density	Helium	G-W	O-W	O_W(calc)	scCO2-W
ID	ft	ID		g/cc	%				
176	11725.9	Weber 1	CoLe Plug	2.70	0.40	77.588	40.316	40.32	19.397
187	12178.1	Amsden 1	Core Plug	2.91	5.89	19.724	10.249	10.25	4.931
200	12227.3	Amsden 2	Core Plug	2.85	2.60	10.837	5.631	5.63	2.709
206	12301.0	Madison	Core Plug	2.74	1.90	403.734	209.786	209.79	100.934
214	12333.9	Madison 1	Core Plug	2.83		488.533	253.849	253.85	122.133
B1	6300-6330	Baxter 1	Cuttings	2.59		52.543	27.302	27.30	13.136
B2	7680-7710	Baxter 2	Cuttings	2.57		29.237	15.192	15.19	7.309
B3	7590-7620	Baxter 3	Cuttings	2.49		57.953	30.113	30.11	14.488
M1	8130-8160	Mowry 1	Cuttings	2.51		94.343	49.022	49.02	23.586
M1	8220-8250	Mowry 2	Cuttings	2.50		138.941	72.196	72.20	34.735
GS1	9190-9200	Gypsum Springs 1	Cuttings	2.59		114.438	59.464	59.46	28.609
P1	11040-11050	Phosphoria 1	Cuttings	2.71		47.705	24.788	24.79	11.926
P2	11140-11150	Phosphoria 2	Cuttings	2.65		52.451	27.254	27.25	13.113
1	10601.9	Red Peak	Core Plug		1.60	126.463	65.712	65.71	31.616
4	10605.9	Red Peak	Core Plug		1.60	153.419	79.719	79.72	38.355
16	10656.4	Red Peak	Core Plug		1.00	365.918	190.136	190.14	91.479
18	10682.1	Red Peak	Core Plug		1.20	204.693	106.362	106.36	51.173
26	11209.9	Weber	Core Plug		8.10	1.050	0.545	0.55	0.262
27	11227.1	Weber	Core Plug		7.60	4.710	2.448	2.45	1.178
45	11766.8	Weber	Core Plug		1.30	139.154	72.306	72.31	34.788
53	12197.4	Amsden	Core Plug		5.80	185.852	96.572	96.57	46.463
59	12250.0	Madison	Core Plug		1.30	168.761	87.691	87.69	42.190
72	12348.9	Madison	Core Plug		18.10	2.961	1.538	1.54	0.740
79	12354.7	Madison	Core Plug		23.50	4.710	2.448	2.45	1.178
99	12399.0	Madison	Core Plug		11.60	4.979	2.587	2.59	1.245
106	12415.1	Madison	Core Plug		18.50	1.225	0.636	0.64	0.306
110	12480.5	Madison	Core Plug		11.80	0.684	0.355	0.36	0.171

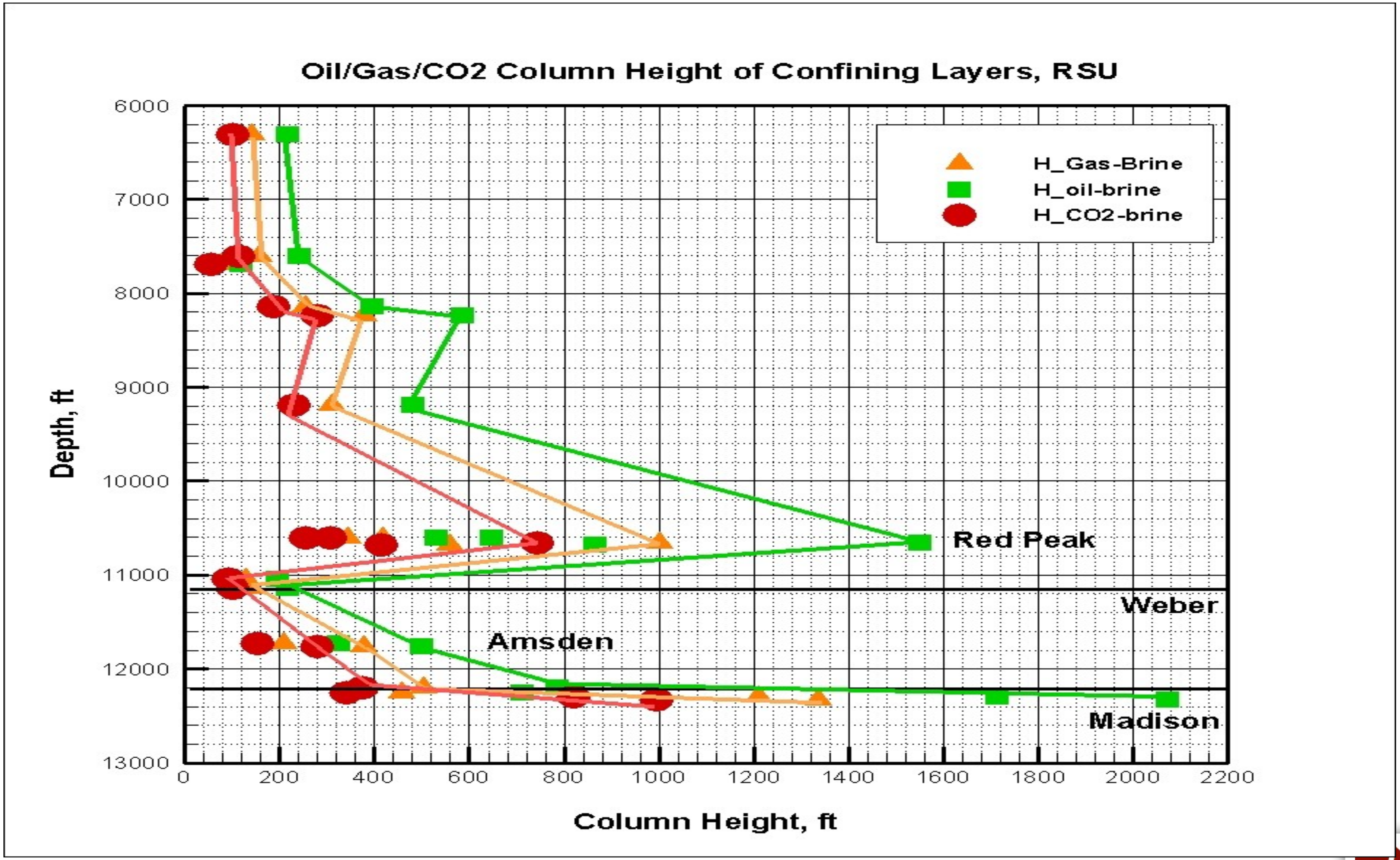
Entry Pressures Derived from High-Pressure Mercury Injection Test Results (Reservoir Condition)



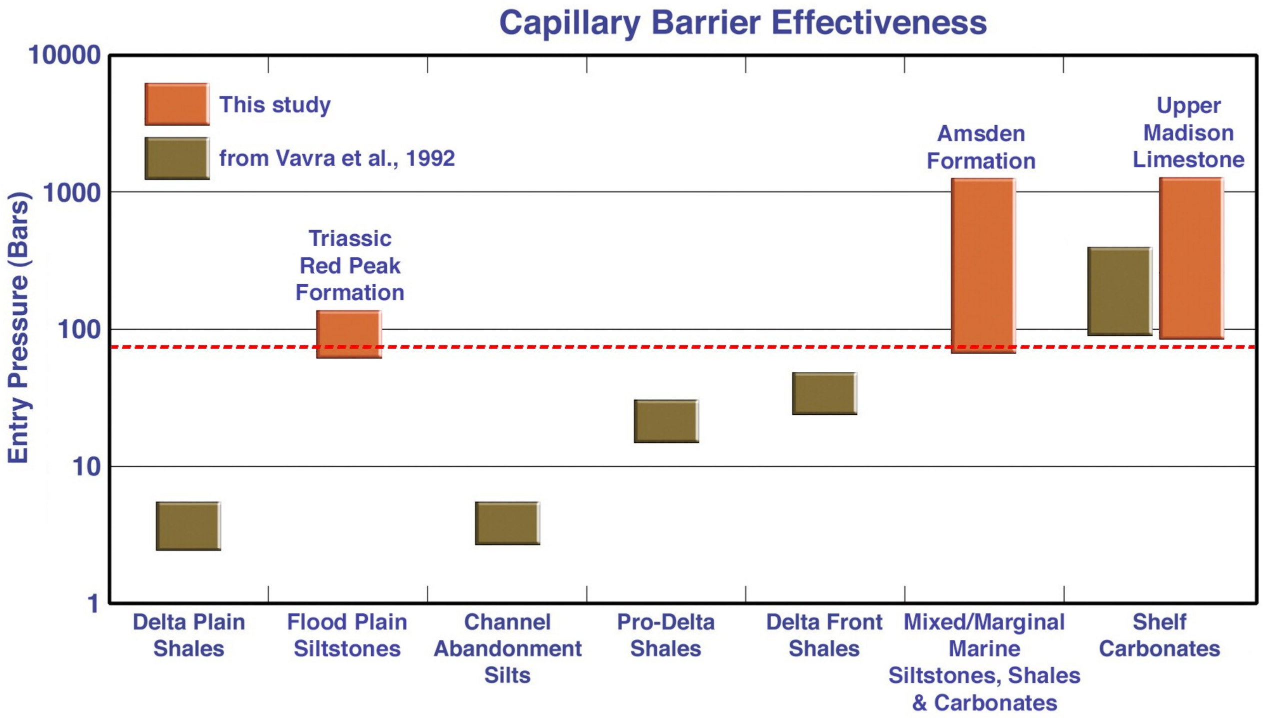
Column Height Derived from High-Pressure Mercury Injection Test Results (Reservoir Condition)

	Interral		Sample	Corumn Height (res)		
Sample	Depth	Formatio	Type	G-W	O-W	CO2-W
ID	ft	ID		ft	ft	ft
Containment Layer						
214.00	12333.90	Madison 1	Core Plug	1335.15	2072.96	994.26
206.00	12301.00	Madison	Core Plug	1209.58	1712.17	820.71
16.00	10656.40	Red Peak	Core Plug	1001.93	1551.25	743.28
18.00	10682.10	Red Peak	Core Plug	558.66	865.16	413.19
53.00	12197.40	Amsden	Core Plug	502.97	784.92	374.55
59.00	12250.00	Madison	Core Plug	455.98	712.19	339.56
4.00	10605.90	Red Peak	Core Plug	417.69	646.97	308.21
45.00	11766.80	Weber	Core Plug	378.47	500.98	279.01
M1	8220-8250	Mowry 2	Cuttings	377.89	585.36	278.57
1.00	10601.90	Red Peak	Core Plug	343.58	532.26	253.02
GS1	9190-9200	Gypsum S	Cuttings	310.52	481.09	228.40
M1	8130-8160	Mowry 1	Cuttings	255.27	395.58	187.26
176.00	11725.90	WebeR 1	CoLe Plug	209.20	324.28	152.96
B3	7590-7620	Baxter 3	Cuttings	155.22	240.72	112.76
B1	6300-6330	Baxter 1	Cuttings	140.34	217.70	101.68
P2	11140-111	Phosphori	Cuttings	140.09	217.31	101.49
P1	11040-110	Phosphori	Cuttings	127.04	197.11	91.78
B2	7680-7710	Baxter 2	Cuttings	76.27	118.52	53.96

Column Height Derived from High-Pressure Mercury Injection Test Results (Reservoir Condition)



Displacement Pressures of Selected Sealing Units Relative to Lithologies



The dashed line indicates displacement pressure needed to retain a 300’ column of injected gas.

From J.F. McLaughlin, et al., 2014

Remarks

- For the targeted Paleozoic storage reservoirs, the confining layers are shale/siltstones of the Chugwater Group (Red Peak Fm.) and the Amsden Formation, and the most upper portion of the Madison Limestone.
- The CO_2 column heights that the various confining layers at the RSU can hold range from 50 ft to 990 ft.
- CO_2 column heights (held by same confining layer) are only about half of the height of an oil column, and three-quarters of the gas column.
- It is potentially disastrous risk to assume that a confining layer which has successfully trapped hydrocarbons over million years, could also contain similar volumes of injected CO_2.
- CO_2 injection simulations for the Madison Limestone and Weber Sandstone reservoirs indicate that CO_2 column heights could rise to 500 ft in the Madison Limestone and 400 ft in the Weber Sandstone. This study shows that confining layers at the RSU storage site have adequate sealing capacity to safely hold the CO_2 columns after injected 50 Mt of supercritical CO_2 in the Madison Limestone and the Weber Sandstone.

Acknowledgement

We would like to acknowledge the support of DOE (DE-FE0009202) in funding and guiding this project