Borehole Elemental Concentration Logs Now Available: A New Source of Geochemistry Data

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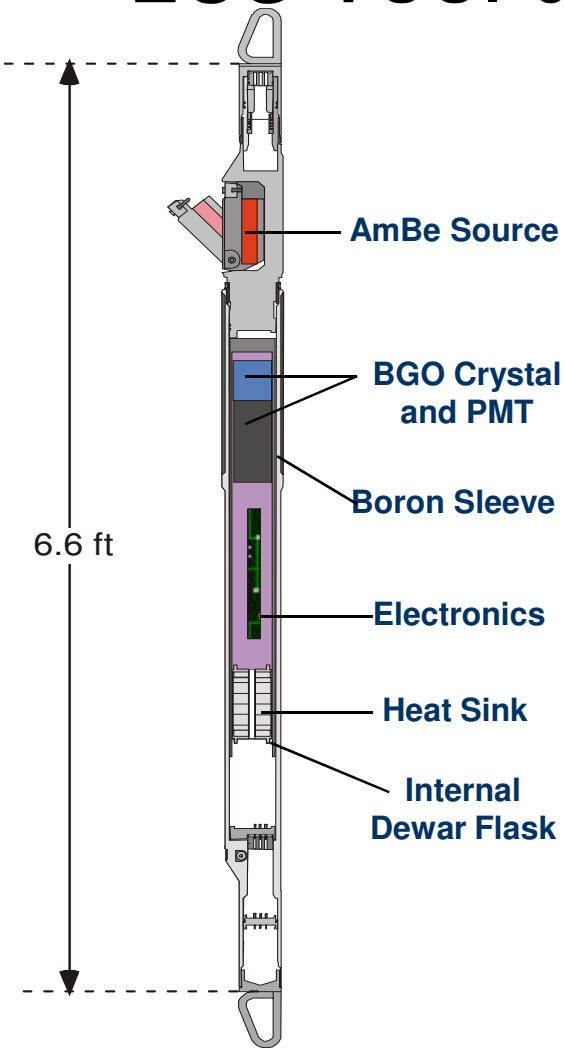
Schlumberger-Doll Research

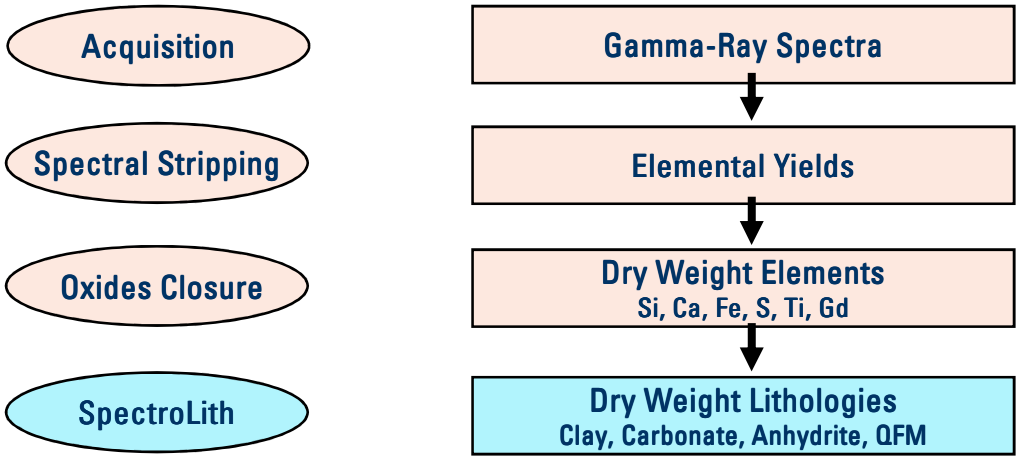
Leaps of Science Follow New Analytical Capabilities

- Well logging provides more data every day about earth formations than all laboratory sources in a year
- Geochemical well logging is a new analytical capability
- Time for earth scientists to address this new source of data

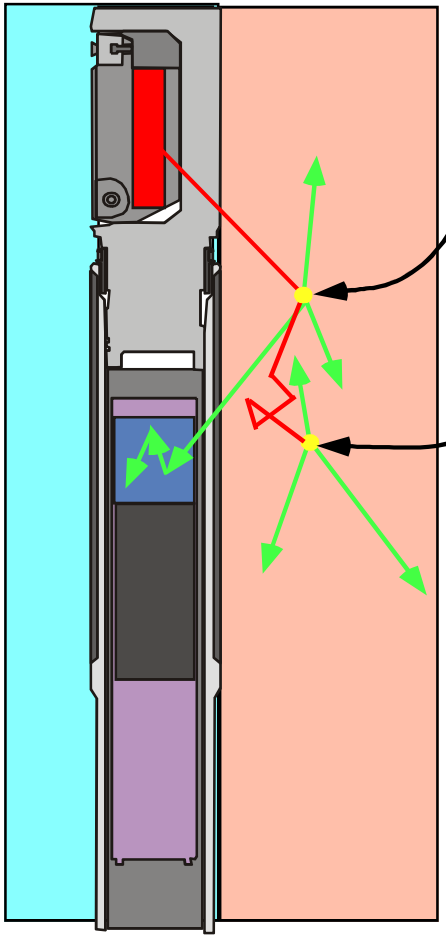
ECS Tool and Data Processing Flow



- Logging Speed: 1800 ft/hr
- Vertical Resolution: 1.5 ft
- Borehole Fluid: All
- Tool Size: 5.0 in O. D.
- Length: 6.6 ft
- Maximum Temp: 350 °F
- Maximum Pressure: 20,000 psi
- Min Hole Size: 6.00 in



What Do We Measure ?

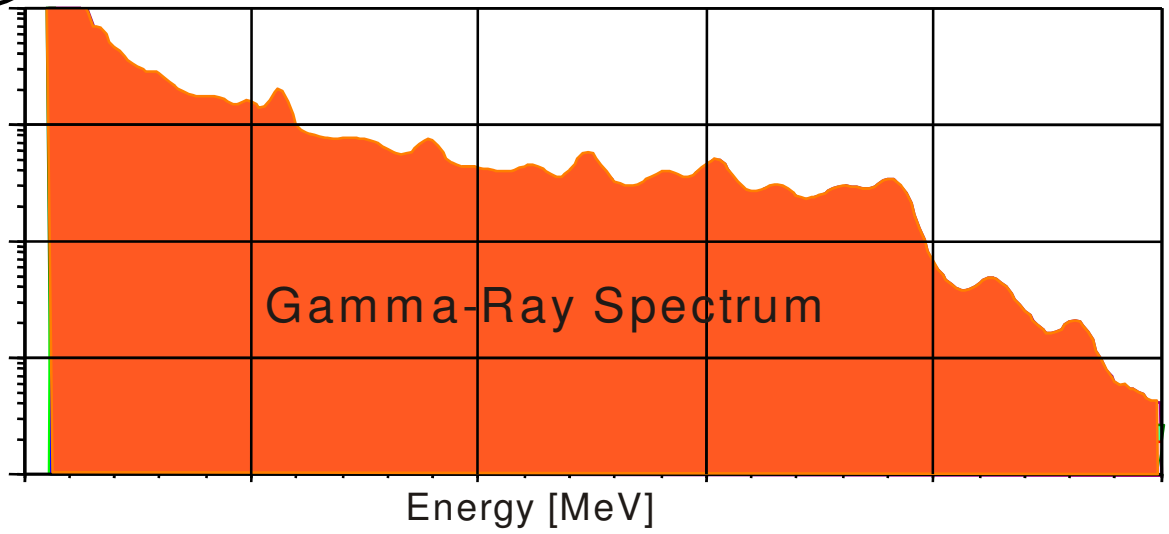


4 MeV neutron interacts with fomation:

Inelastic Interaction (multiple gamma-rays)

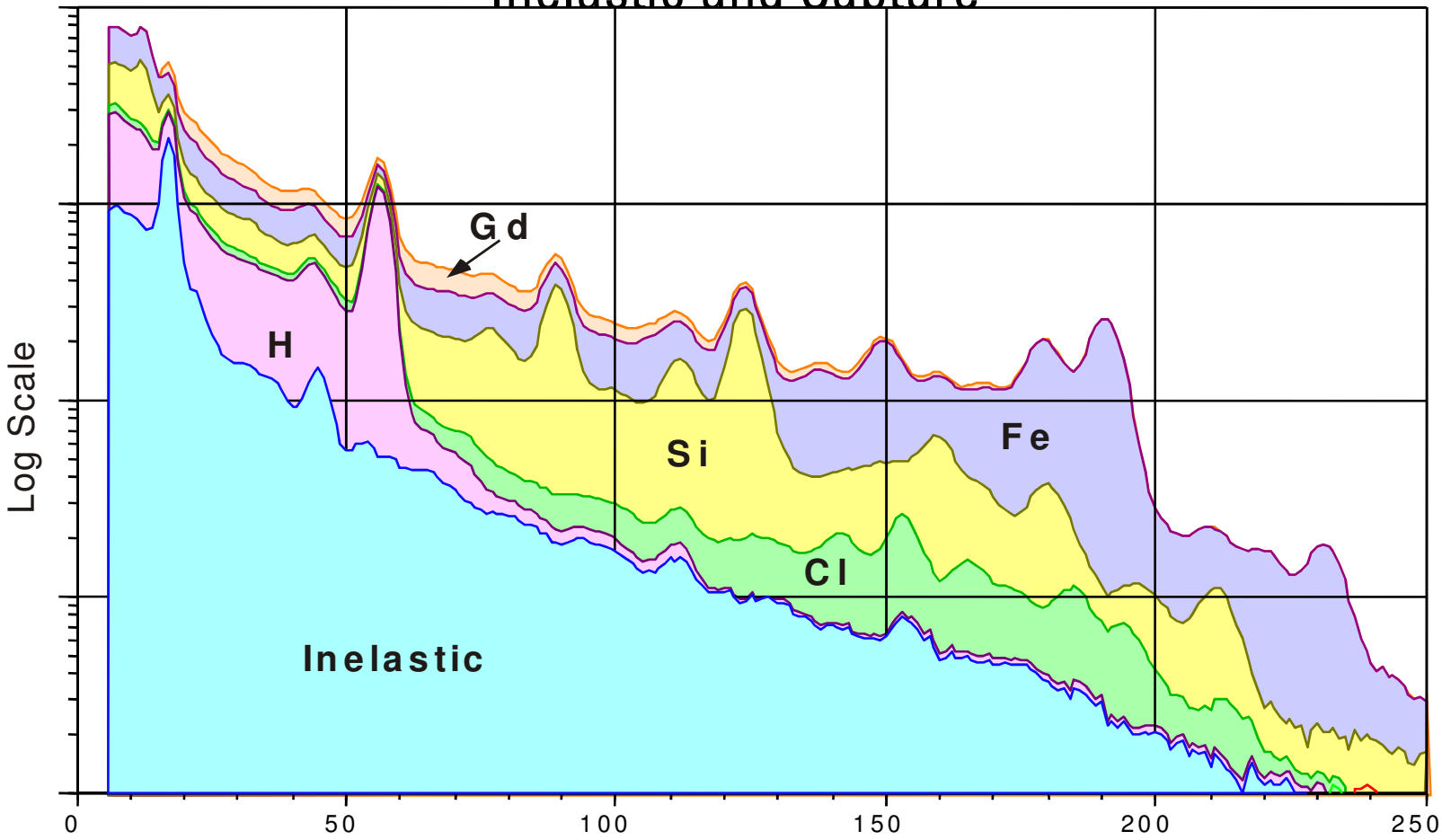
Slowing down of neutron through multiple scattering

Neutron Capture (multiple gamma-rays)

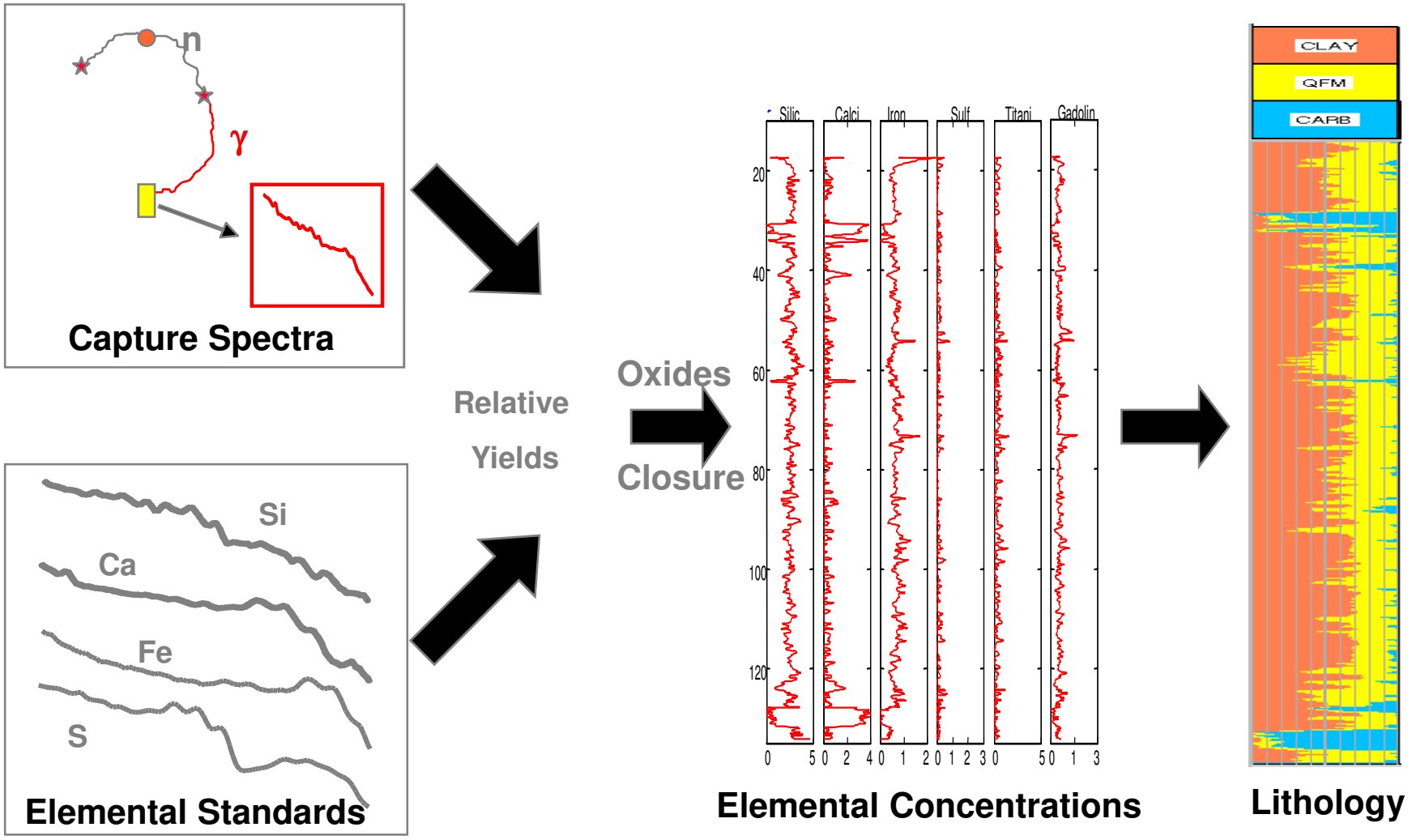


ECS Gamma-Ray Spectrum

Inelastic and Capture

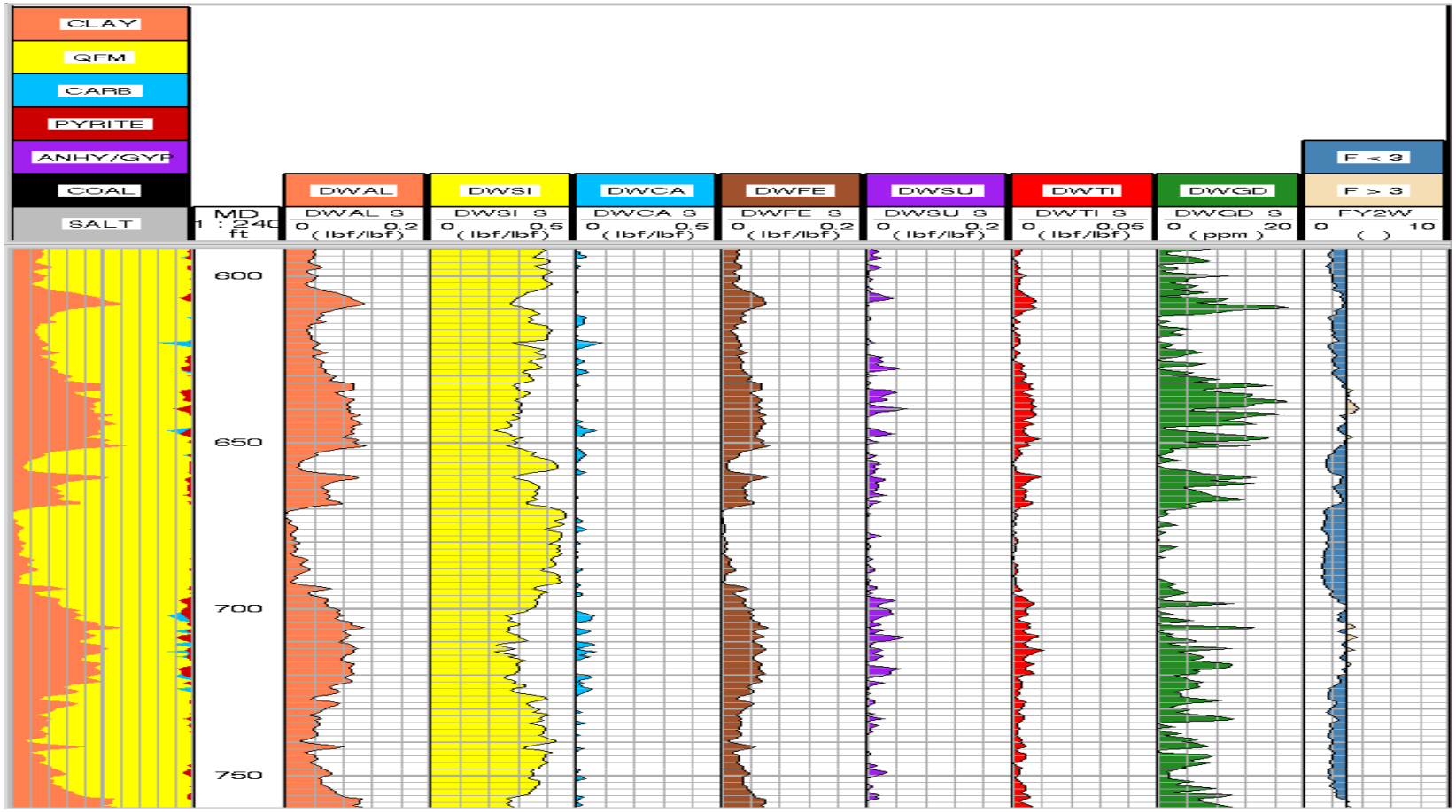


Capture Gamma-Ray Spectroscopy

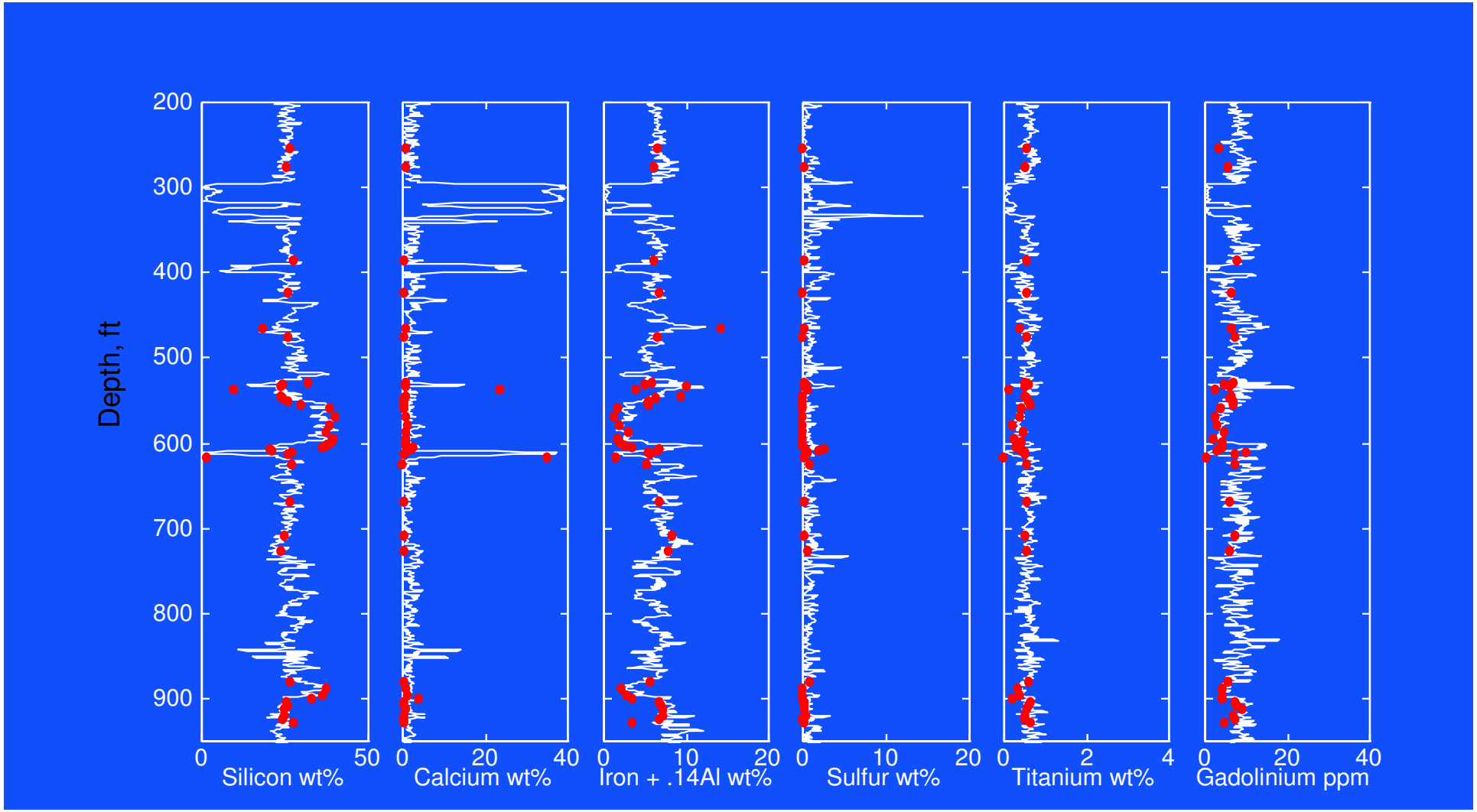


ECS SpectroLith

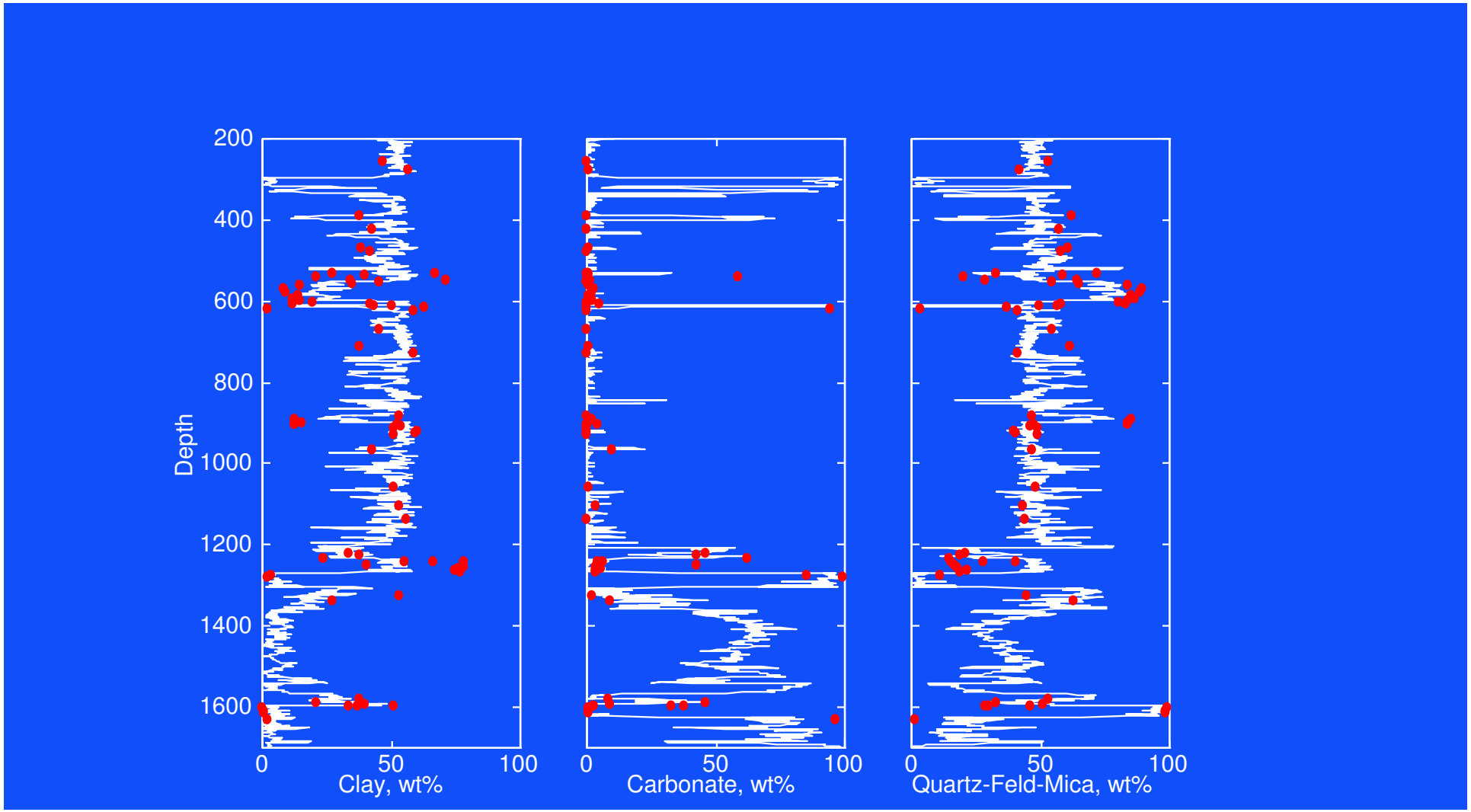
Dry Weight Lithologies and Elements



Open Hole Elemental Concentrations



Open Hole Lithology



DecisionXpress

Instant Petrophysical Evaluation

Nuclear spectroscopy
SLB exclusive hardware and interpretation

+

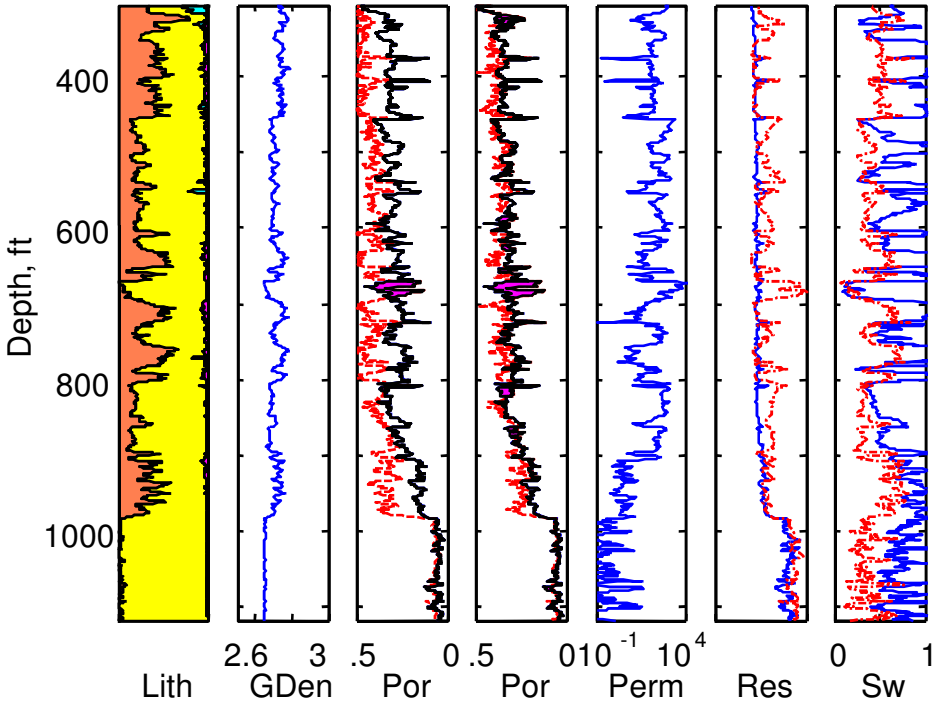
Triple Combo

=

Real-Time Petrophysics

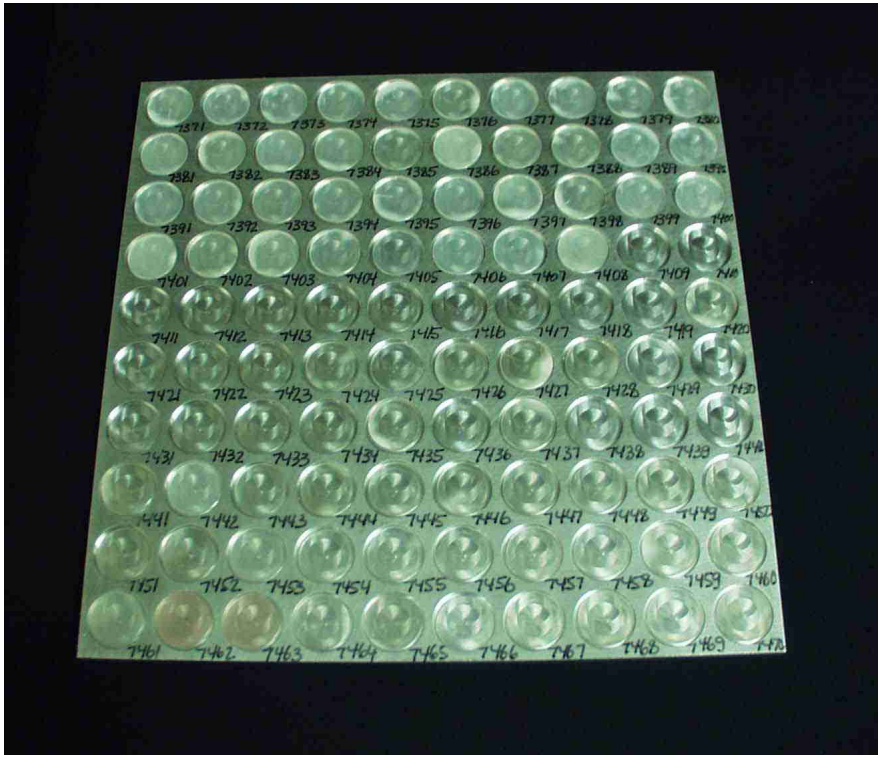
Wireline & LWD

Siliciclastics – Four patented applications



SDR Fourier Transform Infrared Spectroscopy Quantitative Mineralogy

- Recognized world-class
- Patented
- Best paper 1997 Society of Core Analysts



Commercial XRD and Actual Mineralogy

Sample A	Qtz	Ksp	Plag	Cal	Mg-Cal	Dol	Sid	Py	Kaol	2:1 Al clay	2:1 Fe clay	Fe-Chl
Actual	25	5	5	5	0	0	0	0	15	20	20	5
Vendor 1	68	3	4	5	0	0	0	0	8	11		0
Vendor 2	44	1	5	2	0.1	0	0.1		23	12		11
Vendor 3	41	2	3	9	0	0	0	0	36	9		0
Sample B	Qtz	Ksp	Plag	Cal	Mg-Cal	Dol	Sid	Py	Kaol	2:1 Al clay	2:1 Fe clay	Fe-Chl
Actual	30	5	10	5	0	5	0	5	20	10	0	10
Vendor 1	56	0	7	3	0	6	0	14	12	2		1
Vendor 2	34	1	8	3	0	6	0	4	24	2		18
Vendor 3	52	2	3	13	0	0	0	2	24	5		0
Sample C	Qtz	Ksp	Plag	Cal	Mg-Cal	Dol	Sid	Py	Kaol	2:1 Al clay	2:1 Fe clay	Fe-Chl
Actual	30	10	5	5	5	5	10	0	10	15	0	5
Vendor 1	63	3	14	3	0	5	6	0	5	1		0
Vendor 2	39	2	6	4	0	7	14	0.2	15	4		10
Vendor 3	37	1	2	8	0	9	19	0	19	5		0

D. McCarty (Chevron)

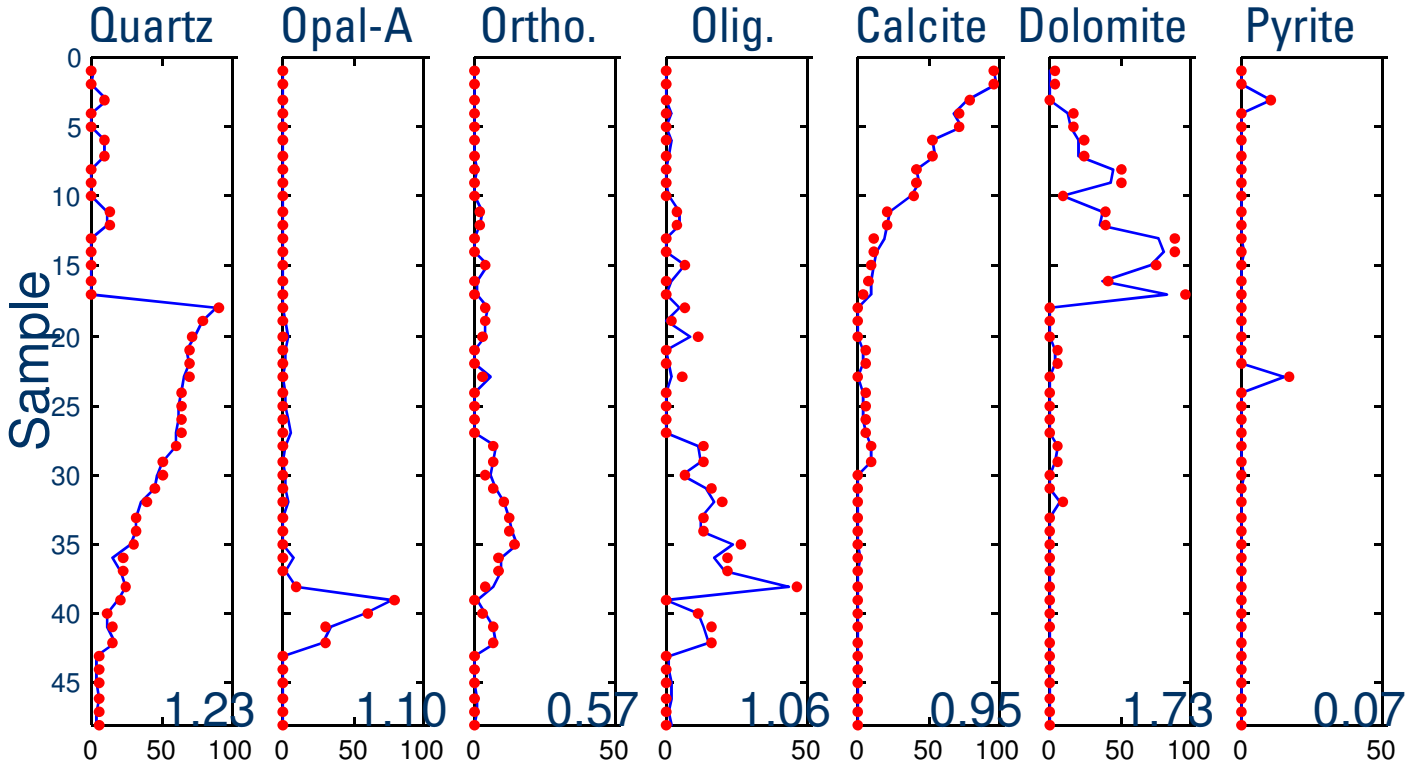
Commercial XRD and Actual Mineralogy

Sample A	Qtz
Actual	25
Vendor 1	68
Vendor 2	44
Vendor 3	41
Sample B	Qtz
Actual	30
Vendor 1	56
Vendor 2	34
Vendor 3	52
Sample C	Qtz
Actual	30
Vendor 1	63
Vendor 2	39
Vendor 3	37

D. McCarty (Chevron)

True and Estimated Mineral Concentrations

True Composition
Estimated from FT-IR



True and Estimated Mineral Concentrations

True Composition
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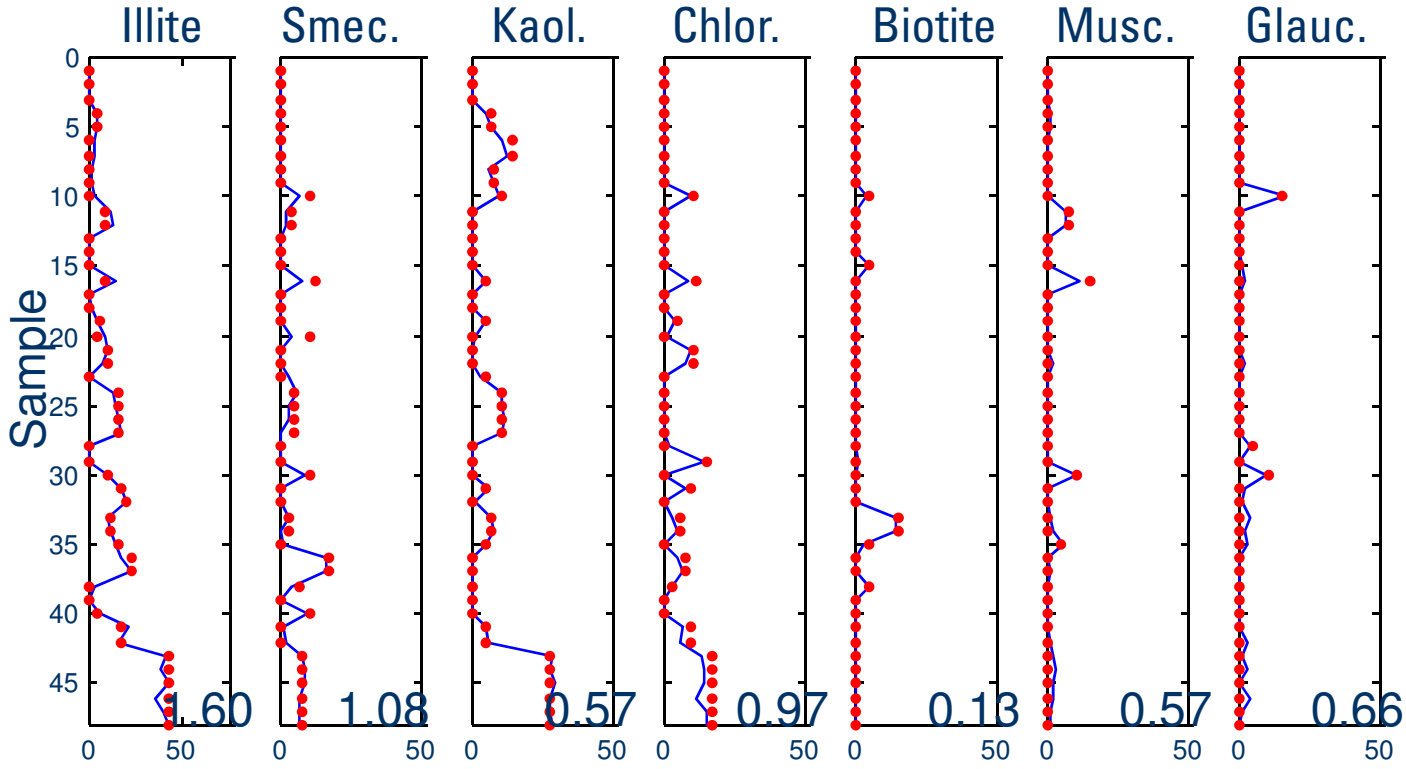


Table 2. Mean and standard deviation of selected elements in the mineral standards. Included are those elements detectable by current geochemical techniques plus Na and B which may exert an additional perturbation on geochemical or other nuclear logging measurements

Mineral (No. samples)	Si (%)	Al (%)	Fe (%)	Ca (%)	Mg (%)	K (%)	Na (%)	Ti (%)	S (%)	LOI (%)	H_2O^+ (%)	Th (ppm)	U (ppm)	Gd (ppm)	B (ppm)
Quartz	46.1	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.01	0.4	0.2	0	0.1	0	0
(2)	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.01		0.1		0	0.1	0	0
Calcite	0.2	0.0	0.1	39.4	0.2	0.0	0.0	0.00	0.05	43.8	0.1	0	1.4	0.5	0.1
(25)	0.1	0.1	0.1	0.6	0.1	0.0	0.0	0.00	0.05	0.3	0.2	0	1.6	0.8	0.4
Dolomite	0.6	0.1	0.7	21.6	12.3	0.0	0.0	0.01	0.07	47.1	0.1	0.1	0.9	1.3	5
(14)	0.5	0.1	1.3	0.4	0.8	0.0	0.0	0.01	0.10	1.2	0.1	0.3	1.6	3.6	7
Siderite	0.4	0.7	40.0	0.3	3.0	0.0	0.4	0.01	0.04	32.5	0.9	0.4	0.5	0.5	0
(2)	0.4	0.7	2.7	0.1	3.9	0.0	0.5	0.00	0.05	2.5		0.5	0.6	0.6	
Na-Plagioclase	30.0	11.8	0.1	2.3	0.1	0.5	7.3	0.01	0.01	0.5	0.2	0	0	0.2	28
(3)	2.0	1.2	0.1	2.0	0.1	0.4	1.4	0.00	0.02	0.2	0.1	0	0	0.4	19
Ca-Plagioclase	21.7	17.7	0.3	12.1	0.3	0.0	1.4	0.02	0.00	0.7	0.3	0	0.1	0.1	11
(4)	1.5	1.0	0.1	1.5	0.1	0.0	1.0	0.01	0.00	0.2	0.1	0	0.1	0.1	10
K-Feldspar	30.0	10.0	0.2	0.1	0.0	10.2	2.0	0.01	0.00	0.5	0.4	1.1	0.4	0.3	21
(6)	0.3	0.1	0.2	0.1	0.0	0.6	0.4	0.00	0.00	0.3	0.1	1.1	0.5	0.4	34
Opal	40.0	1.4	0.5	0.5	0.3	0.5	0.7	0.10	0.35	6.5	4.2	4.7	6.5	1.3	160
(1)															
Muscovite	21.2	19.1	1.3	0.1	0.1	7.8	0.5	0.03	0.04	4.8	3.5	0	0.7	0.0	450
(2)	0.6	0.6	0.8	0.1	0.0	0.5	0.1	0.02	0.05	0.1	1.0	0	0.9		260
Biotite	18.2	6.0	13.6	0.2	7.7	7.2	0.4	1.48	0.07	0.8	1.1	1.5	0.7	0.2	35
(1)															
Kaolinite	20.8	20.4	0.4	0.1	0.1	0.1	0.1	1.13	0.01	14.2	12.9	19	3.2	4	14
(9)	0.4	0.5	0.3	0.1	0.1	0.1	0.1	0.21	0.01	0.3	0.8	6	0.5	2	5
Illite	24.9	10.5	4.8	0.5	1.2	4.5	0.4	0.50	0.6	9.9	5.5	12	4.8	4	163
(6)	1.8	0.8	0.9	0.5	0.3	1.0	0.2	0.07	0.5	2.1	0.6	2	4.6	2	47
Glauconite	23.1	4.4	15.5	0.5	2.1	5.9	0.0	0.09	0.1	8.3	6.1	3	5.4	4	500
(1)															
Smectite	26.4	9.1	2.0	1.3	2.2	0.6	0.7	0.15	0.02	16.1	5.8	26	7.1	8	21
(8)	1.6	0.9	1.5	0.5	0.9	0.8	0.6	0.10	0.03	4.7	1.4	7	6.3	2	16
Chlorite, all	14.0	9.6	20.8	0.7	4.8	0.4	0.1	1.32	0.1	8.8	9.2	7	2.9	5	20
(5)	3.5	0.8	5.5	0.9	3.4	0.5	0.2	1.06	0.1	2.0	2.1	8	2.2	5	25
Chlorite, Sed.	17.9	9.0	16.4	1.6	2.5	0.9	0.3	2.37	0.2	8.1	7.0	16	4.2	10	47
(2)	0.3	0.8	0.2	0.8	0.1	0.2	0.1	0.30	0.2	0.8	0.3	1	0.5	0.3	3

Table 3. Mean and standard deviation of γ-ray, Σ, and the P_e of the standard mineral samples. Also shown are the values of Σ and the values of p_e obtained using the chemical formula (Ellis *et al.*, 1988)

Mineral (No. samples)	Computed GR_{mat} (API)	Computed $Sigma_{mat}$ (cu)	Formula $Sigma_{mat}$* (cu)	Computed P_e (peu)	Formula P_e* (peu)
Kaolinite	104	20.1	13.04	2.1	1.49
(9)	22	2.1		0.2	
Illite	160	40.6	16.74	4.0	3.03
(6)	37	5.6		0.2	
Smectite	168	20.0	8.34‡	2.9	1.63‡
(8)	71	2.3		0.4	
Chlorite, all	56	43.7	47.44§	8.1	12.36§
(5)	53	7.8		1.2	
Chlorite, Sed.	111	50.5	47.44§	7.8	12.36§
(2)	13	0.8		0.1	
Glauconite	150	89.6	20.89	6.7	4.79
(1)					
Muscovite	130	95.3	17.06	4.0	2.40
(2)	0	38.7		1.1	
Biotite	127	54.1	35.09	7.0	8.70
(1)					
K-Feldspar	171	15.3	15.82	3.4	2.86
(6)	7	2.8		0.6	
Na-Plagioclase	8	11.4	7.64	2.1	1.68
(3)	6	2.5		0.2	
Ca-Plagioclase	1	9.4	7.38	3.0	3.13
(4)	1	1.2		0.2	
Quartz	1	4.7	4.55	1.9	1.81
(2)	1	0.1		0.0	
Opal	79	22.6	5.26	2.5	1.75
(1)					
Calcite	11	7.4	7.08	5.2	5.08
(25)	13	2.1		0.4	
Dolomite	8	6.9	4.7	3.4	3.14
(14)	13	3.3		0.4	
Siderite	6	54.2	52.78	18.6	14.69
(2)	8	8.9		9.5	

* Ellis *et al.* (1988).
† Peu = barns/electron.
‡ Montmorillonite—no interlayer water.
§ Fe-chlorite.

Table 4. Mean and standard deviation of thermal neutron porosity (TNPH) and epithermal (ENPH) neutron porosities of the mineral standard samples. Also shown are the values calculated by Ellis *et al.* (1988) from mineral formulae

Mineral (No. samples)	Computed TNPH* (ls units)§	Formula TNPH† (ls units)	Computed ENPH‡ (ls units)	Formula ENPH† (ls units)
Kaolinite	45.0	45.1	43.3	47.8
(9)	3.2		2.9	
Illite	24.7	15.8	17.6	12.7
(6)	2.8		2.6	
Smectite	21.8	11.5¶	17.8	12.6¶
(8)	6.0		6.1	
Chlorite, all	>48.2	>60**	61.0	>60**
(5)			17.6	
Chlorite, Sed.	>48.2	>60**	42.9	>60**
(2)			1.8	
Glauconite	—††	17.5	20.2	13.2
(1)				
Muscovite	>20.8	16.5	10.7	13.4
(2)			3.2	
Biotite	11	15.5	5.2	13.1
(1)				
K-Feldspar	−0.6	−1.1	−1.0	−1.5
(6)	0.6		0.3	
Na-Plagioclase	−0.5	−1.3	−0.8	−1.0
(3)	0.5		0.2	
Ca-Plagioclase	−0.8	−1.6	−0.7	−1.3
(4)	0.4		0.4	
Quartz	−1.8	−2.1	−0.8	−1.1
(2)	0.3		0.4	
Opal	8.5	1.9	4.7	3.3
(1)				
Calcite	0.2	0.0	0.0	0.0
(25)	0.3		0.2	
Dolomite	1.5	0.5	1.7	1.7
(14)	1.1		0.3	
Siderite	18.4	12.9	11.1	6.3
(2)	7.3		6.5	

* Thermal neutron porosity.
† Ellis *et al.* (1988).
‡ Epithermal neutron porosity.
§ Limestone equivalent units.
¶ Montmorillonite—no interlayer water.
** Fe-chlorite.
†† High level of thermal neutron absorbers render calculation meaningless.

Table A2

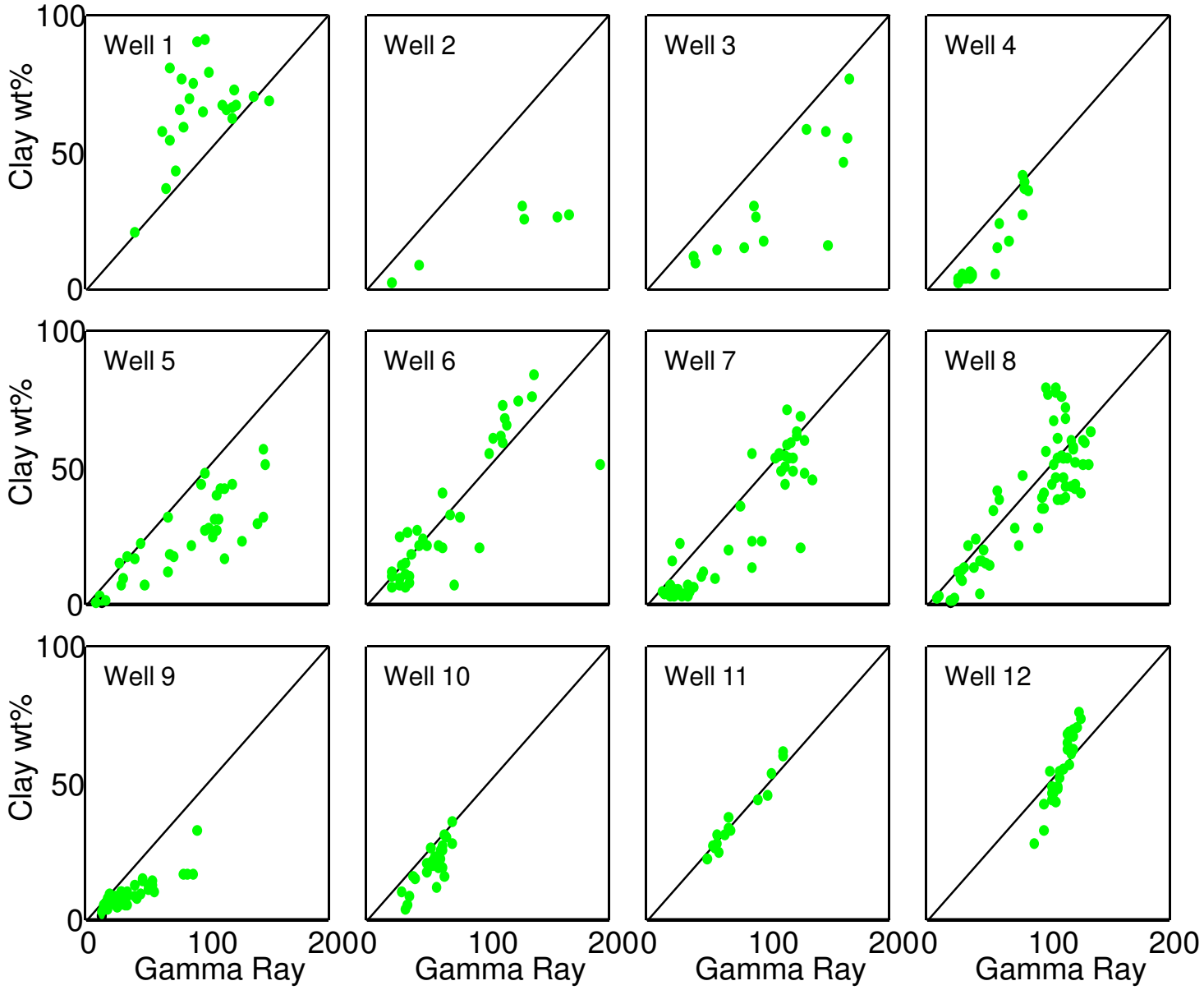
Standard	Li	B	V	Zr	Hf	Th	U	Be	Sc	Cr	Mn	Co	Ni	Cu	Zn	Ga	As	Se	Rb	Sr
	Concentrations in ppm																			
Kaolinite																				
Kao-1	0	14	170	283	10	23	2.7	1	15.5	98	24	2	23	11.8	12	44.9	1.4	0	3	41
Kao-2	40	20	190	282	8.4	21	4.2	3	27.4	110	0	0	17	10.3	33.6	46.6	4.8	1.8	12	39
Kao-3	140	16	94		9	26	2.7	2	14	86	26	11	36	15	28	50	0	0	20	25
Kao-4	0	9.1	220	290	9	21	2.6	1	15	84	6	5	20	10	16	51	2	0	10	40
Kao-5	88	15	130	190	7	12	3.5	2	17	78	10	12	33	12	50	71.8	2	0.5	10	55
Kao-6	92	14	140	193	7	12	3.7	2	17	92	14	12	44	15	62	72.5	4	0.5	12	74
Kao-7	14	22	83	441	11	21	3.3	1	22.5	190	0	21	20	14.8	42.6	41.5	1.4	0	4	60
Kao-8	21	7.7	205	150	4.6	26	3	2	24.1	110	0	14	1	3.2	3.9	50.8	0.9	0	0	5
Kao-9	54	8.9	116	241	7	12	3.5	2	17.1	83	0	29	30	31.1	42.2	64.5	0.9	0	0	134
Average	49.9	14.1	150	259	8.1	19.3	3.2	1.8	19	103	8.9	11.8	24.9	13.7	32	55	1.9	0.3	7.9	53
St dev	48.2	4.9	49	90	1.9	5.8	0.5	0.7	5	34	10.4	9.1	12.6	7.5	19	12	1.5	0.6	6.6	36
Illite																				
Ill-1	22	134	150	165	5.5	12	4	5	17.2	110	89	14	36	46.9	159	27.4	58	0.6	211	205
Ill-2	30	190	1000	147	5	14	14.1	6	19	350	94	17	130	80	100	27.4	23	23	195	933
Ill-3	32	120	150	160	5	12	2.5	7	19	98	620	25	63	55	190	27.8	20	0.5	220	108
Ill-4	40	164	176	132	3.5	9.8	2.3	8	19.3	130	137	16	30	43	218	34	37	0	247	141
Ill-5	36	127	148	177	4.3	12	3.5	5	16.5	100	142	17	29	42.4	177	27.5	52	0	207	176
Ill-6	29	242	126	86	3.4	14	2.4	8	17.8	140	121	23	52	17	76.1	33.4	3.1	0	294	274
Average	32	163	292	145	4.5	12.3	4.8	6.5	18	155	201	18.7	56.7	47.4	153	29.6	32.2	4.0	229	306
Std dev	6	47	347	33	0.9	1.6	4.6	1.4	1	87	207	4.3	38.3	20.4	55	3.2	20.8	9.3	36	312
Smectite																				
Sme-1	9	17	10	148	6.9	34	16.3	3	6.84	4	84	2	3	3.2	76.9	26.9	0.5	0	21	409
Sme-2	9	44	120		4	13	2.6	4	13	10	72	13	7	15	42	25	6.1	0	130	360
Sme-3	45	5.7	32		9	25	1.6	4	6	0	1162	4	6	1.5	79	19	0.8	0	20	90
Sme-4	190	7.4	86		8	25	1.5	4	4	0	774	4	6	1.5	68	21	5.6	0	21	377
Sme-5	24	28	10	190	10	31	11.1	3	6	0	30	30	2	4.5	150	32.1	7.3	0	14	251
Sme-6	200	5.7	80	239	8	23	2.3	5	4	0	774	5	2	0	59	22	4	0	16	415
Sme-7	16	18	14	131	6	33	15.3	3	7	0	66	4	1	1.5	69	31.4	2.6	0	26	363
Sme-8	26	45	16	144	6	21	6	3	4	0	56	5	5	2.5	48	18.8	2.6	0	18	148
Average	65	21	46	170	7.2	26	7.1	3.6	6.4	1.8	377	8.4	4.0	3.7	74.0	24.5	3.7	0.0	33.3	302
Std dev	81	16	43	44	1.9	7	6.3	0.7	3.0	3.6	452	9.3	2.3	4.8	33.4	5.2	2.5	0.0	39.3	124
Chlorite																				
mChl-1	6	1.5	290	54	2	0	0	5	52.3	370	687	210	578	34.3	44	37.1	0.6	0	9	2
mChl-2	15	0.5	460		3	1.7	1.1	9	31	100	2943	0	28	12	99	47	0.1	0	4	2
mChl-3	100	2.3	140	10	0	0.6	5.1	7	0	0	5731	0	5	0	530	59	0.8	0	6	7
Chl-1	92	48.7	501	460	10	17	4.5	6	22	630	697	109	126	32.9	244	40.3	7.3	3	47	132
Chl-2	99	44.9	489	237	5.7	15	3.8	6	23.8	550	1400	85	116	22.9	223	36.3	7.1	0	35	137
Average	62	20	376	190	4.1	6.9	2.9	6.6	26	330	2292	80.8	170.6	20	228	44	3.2	0.6	20.2	56
Std dev	48	25	157	205	3.9	8.4	2.2	1.5	19	275	2131	87.4	233.8	15	188	9	3.7	1.3	19.5	72
Sed Chlorite																				
Chl-1	92	48.7	501	460	10	17	4.5	6	22	630	697	109	126	32.9	244	40.3	7.3	3	47	132
Chl-2	99	44.9	489	237	5.7	15	3.8	6	23.8	550	1400	85	116	22.9	223	36.3	7.1	0	35	137
Average	96	47	495	349	7.9	16.0	4.2	6.0	23	590	1049	97.0	121.0	28	234	38	7.2	1.5	41	135
Std dev	5	3	8	158	3.0	1.4	0.5	0.0	1	57	497	17.0	7.1	7	15	3	0.1	2.1	8	4

continued overleaf

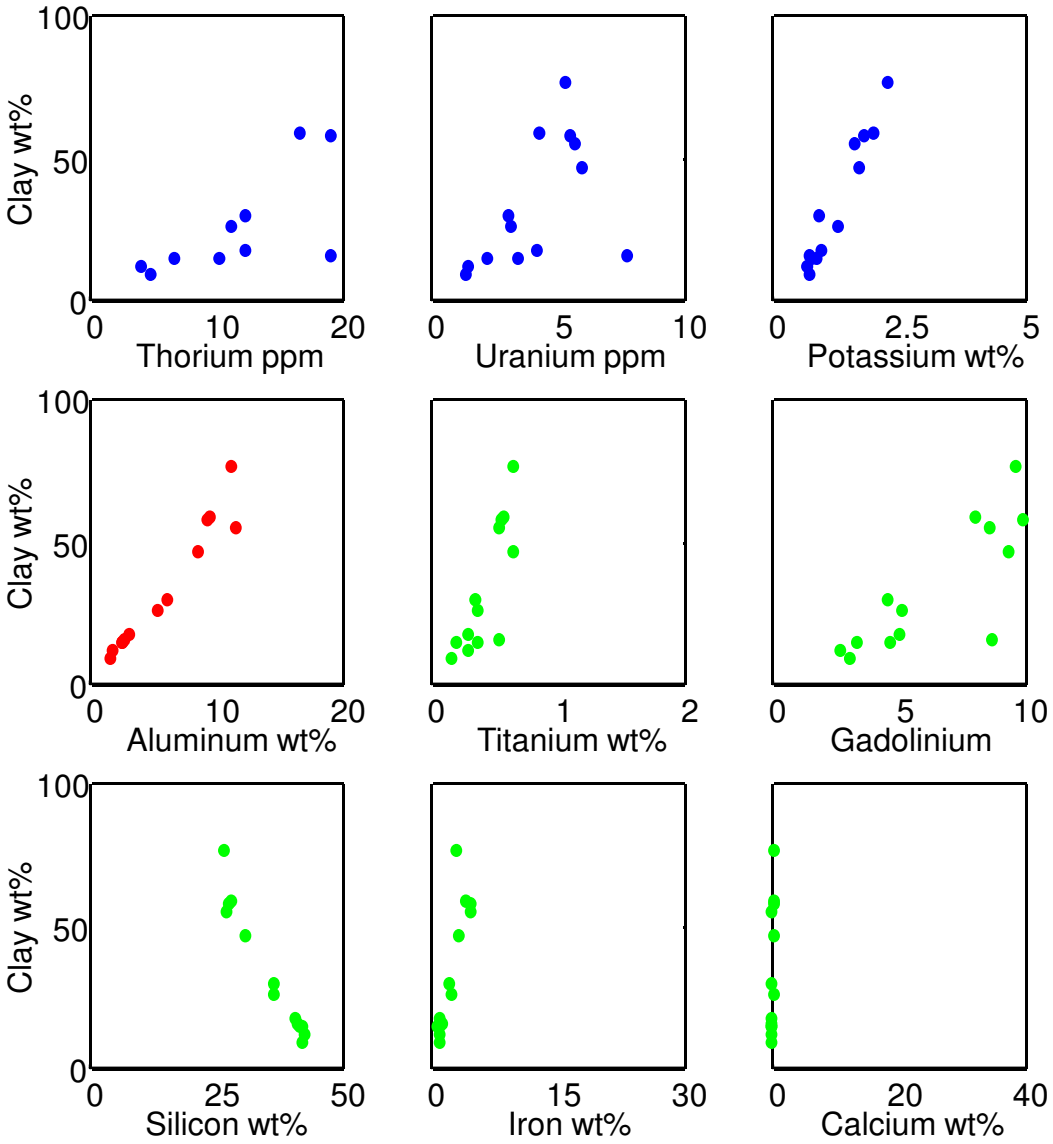
Development of Applications

- Total clay from chemical data
- Matrix density from chemical data
- More for you to develop

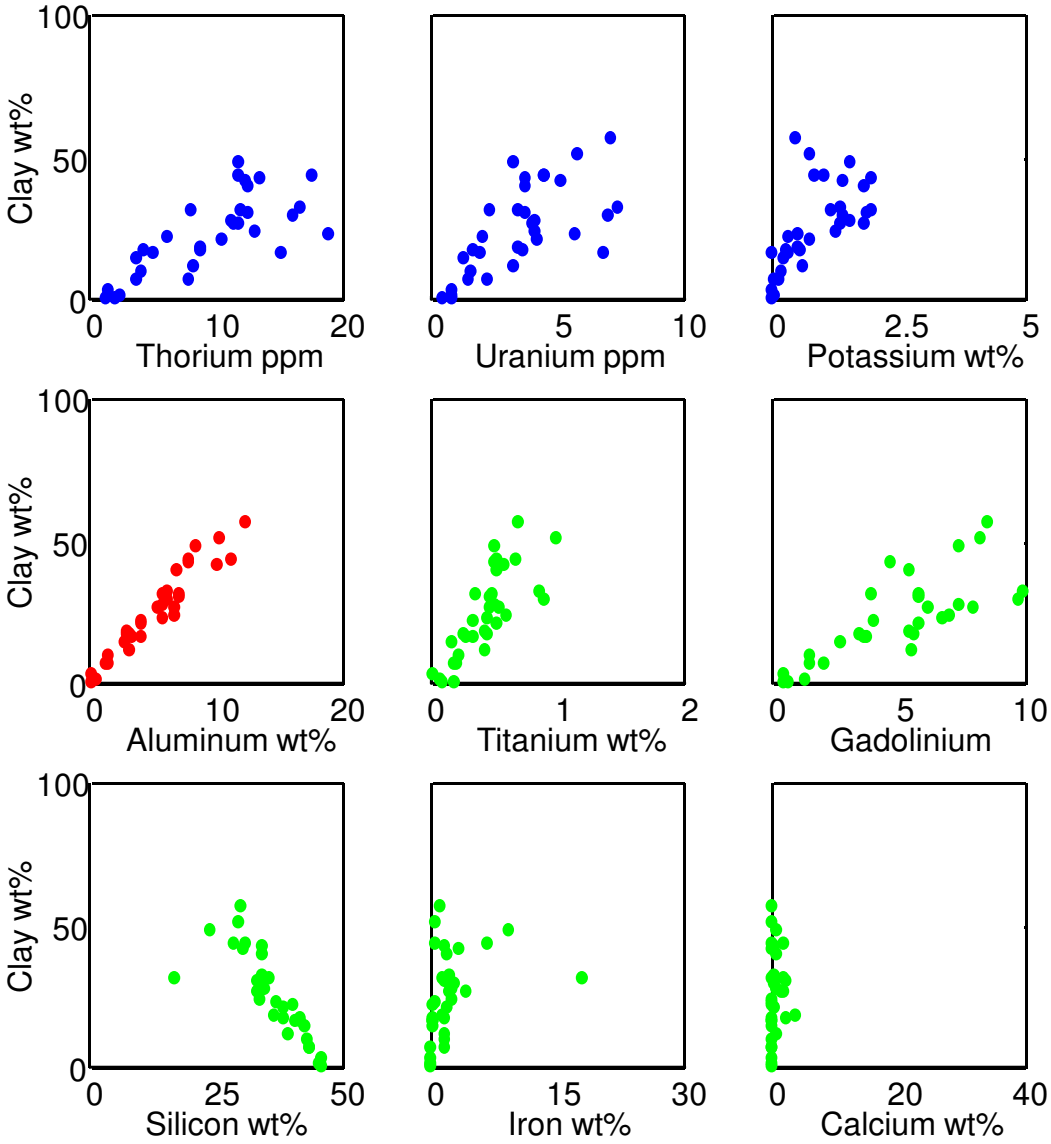
Clay and Gamma Ray



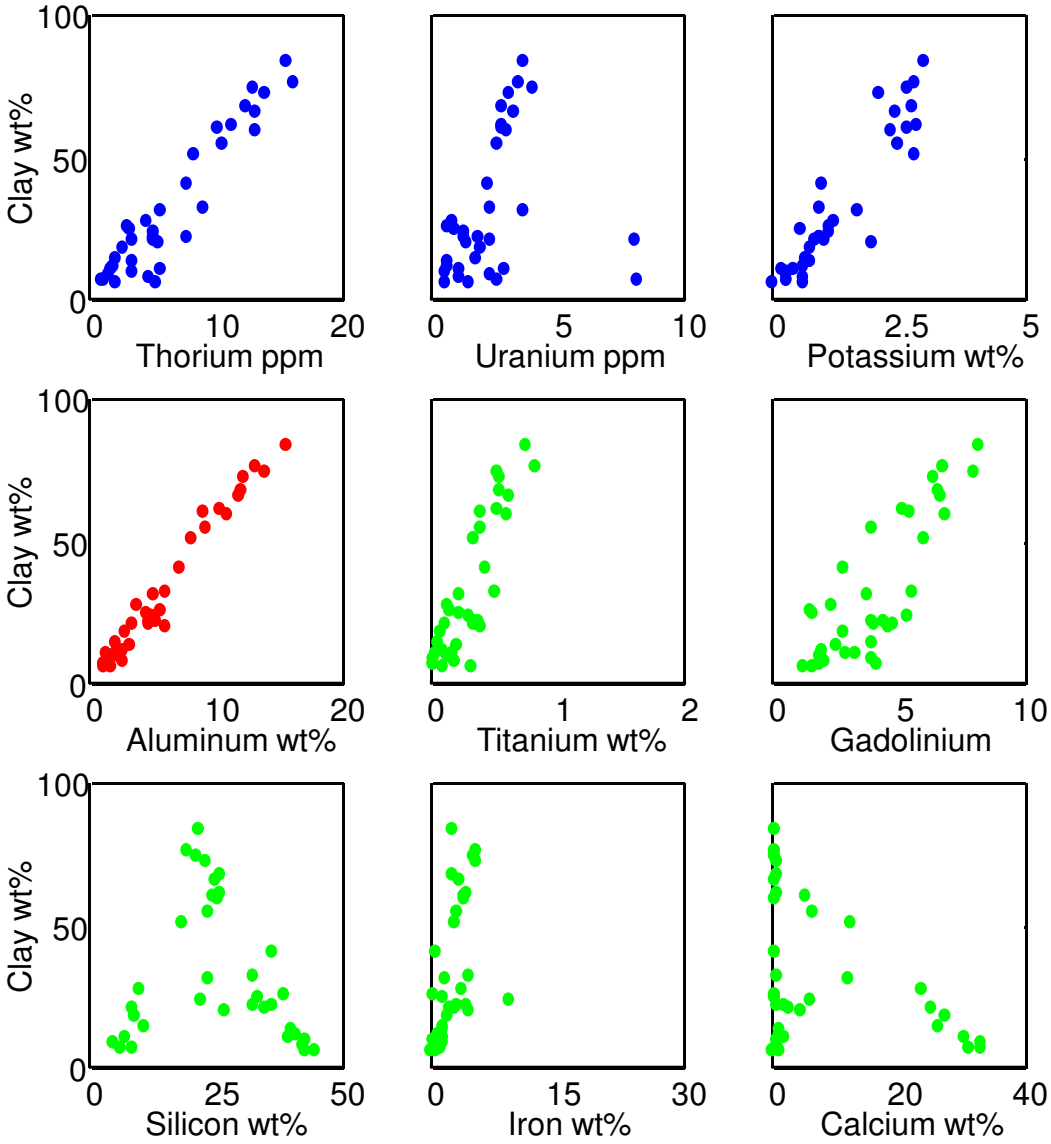
Clay Elemental Relationships - Well 3

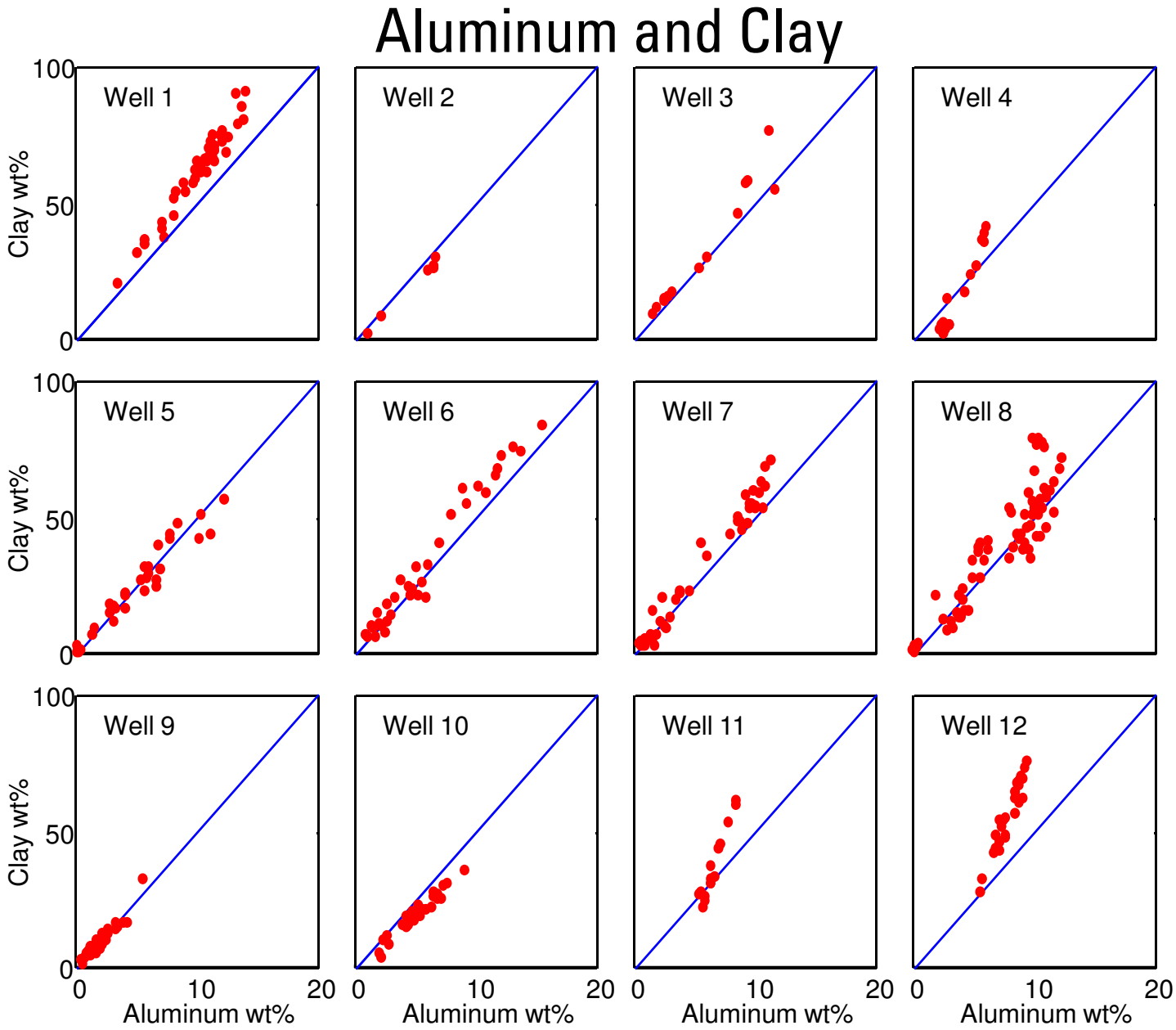


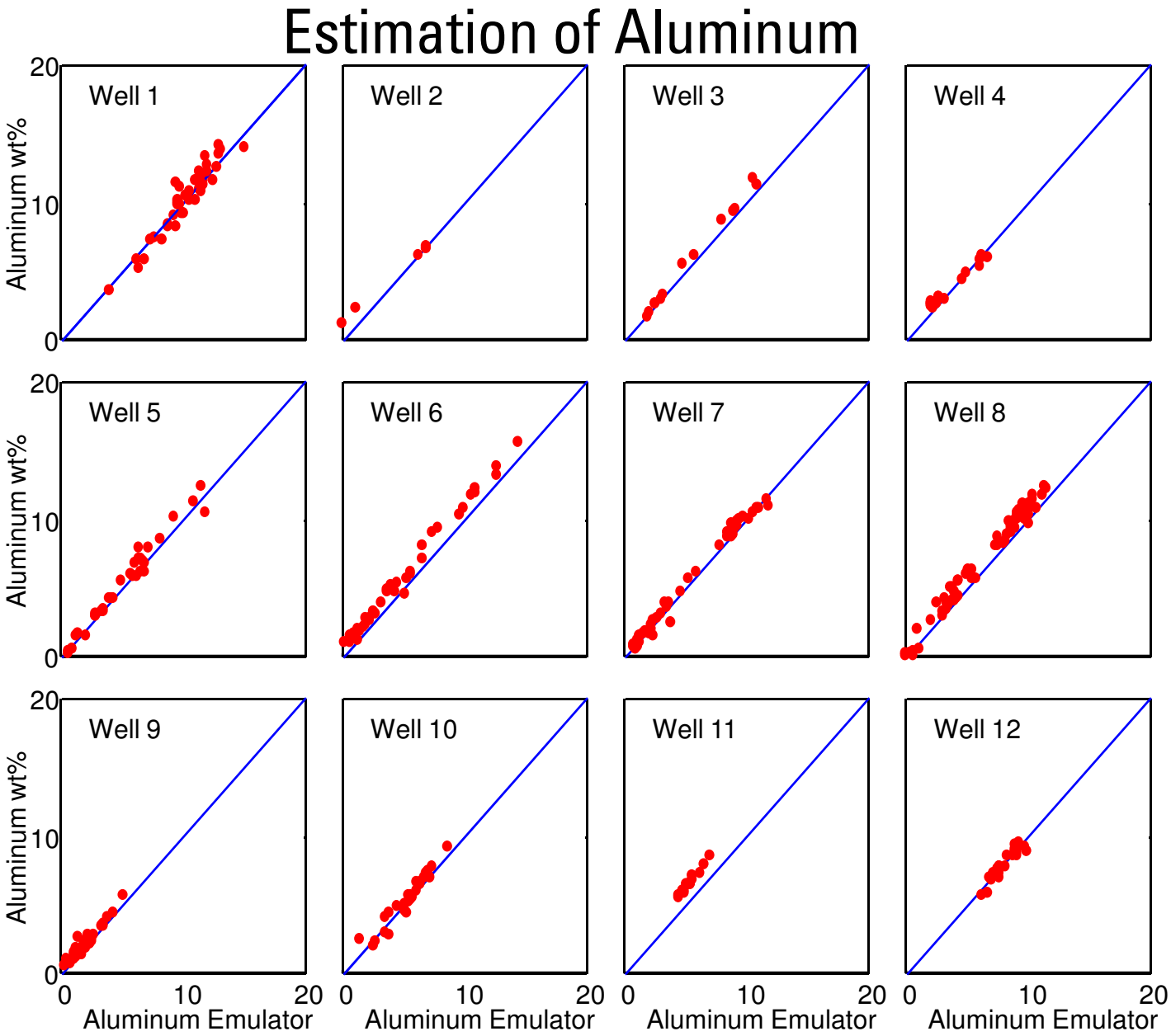
Clay Elemental Relationships - Well 5

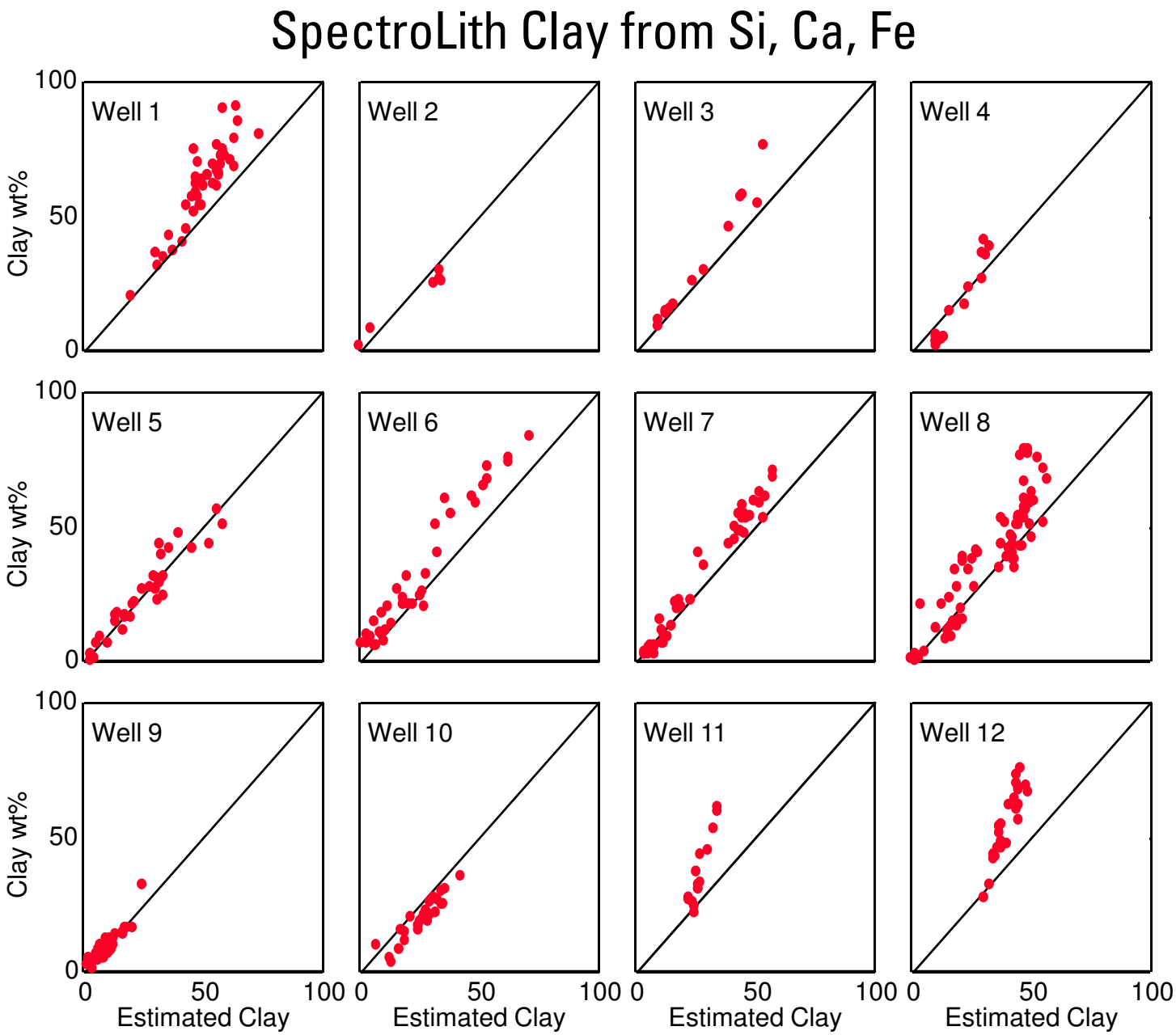


Clay Elemental Relationships - Well 6

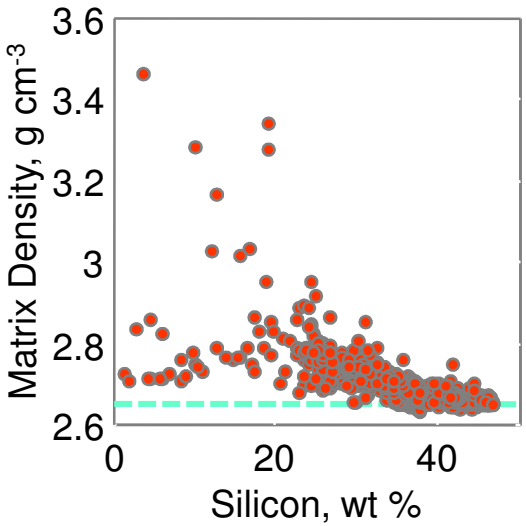



Aluminum and Clay
Well 1
Well 2
Well 3
Well 4
Well 5
Well 6
Well 7
Well 8
Well 9
Well 10
Well 11
Well 12
Clay wt%
Aluminum wt%
0
50
100
0
10
20

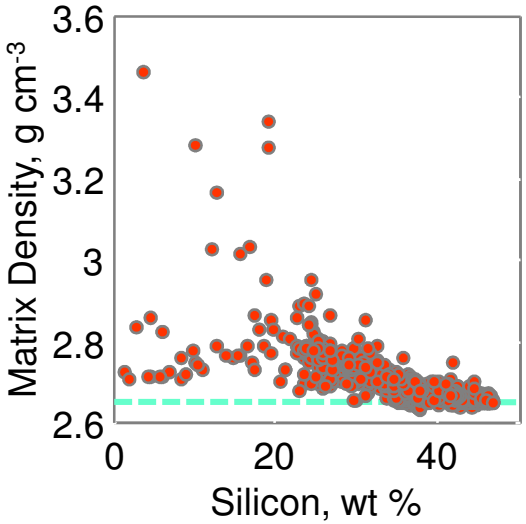

Estimation of Aluminum
Well 1
Well 2
Well 3
Well 4
Well 5
Well 6
Well 7
Well 8
Well 9
Well 10
Well 11
Well 12
Aluminum wt%
Aluminum Emulator
0
10
20

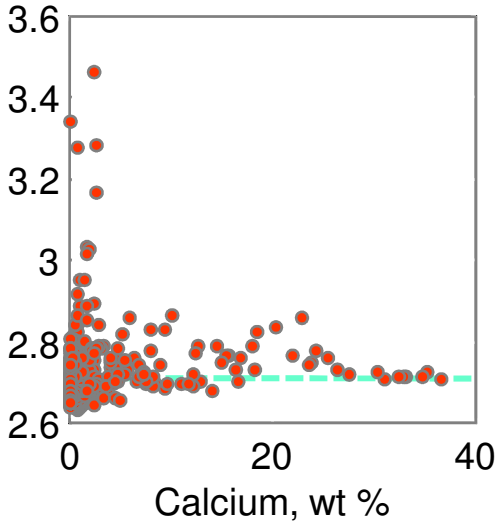

SpectroLith Clay from Si, Ca, Fe
Well 1
Well 2
Well 3
Well 4
Well 5
Well 6
Well 7
Well 8
Well 9
Well 10
Well 11
Well 12
Clay wt%
Estimated Clay
0
50
100

Changes in ρ_{ma} with Silicon

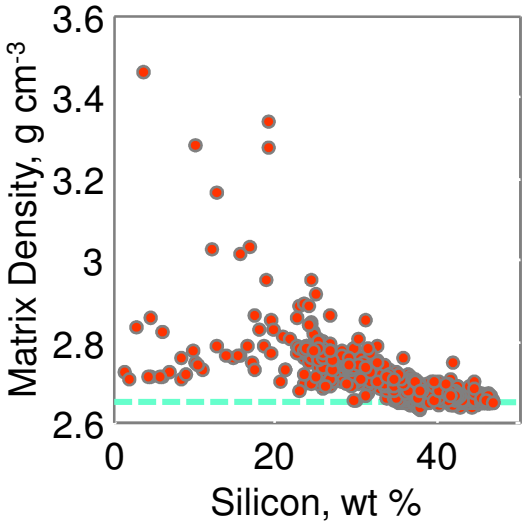


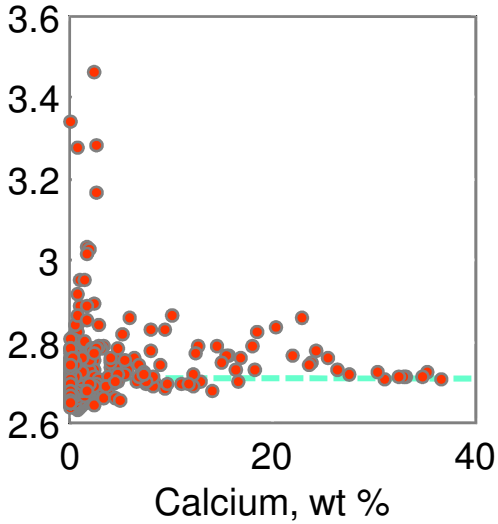
Variation of ρ_{ma} with Calcium

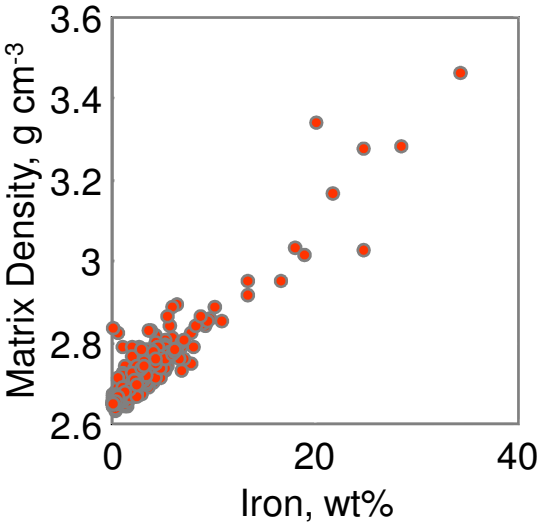




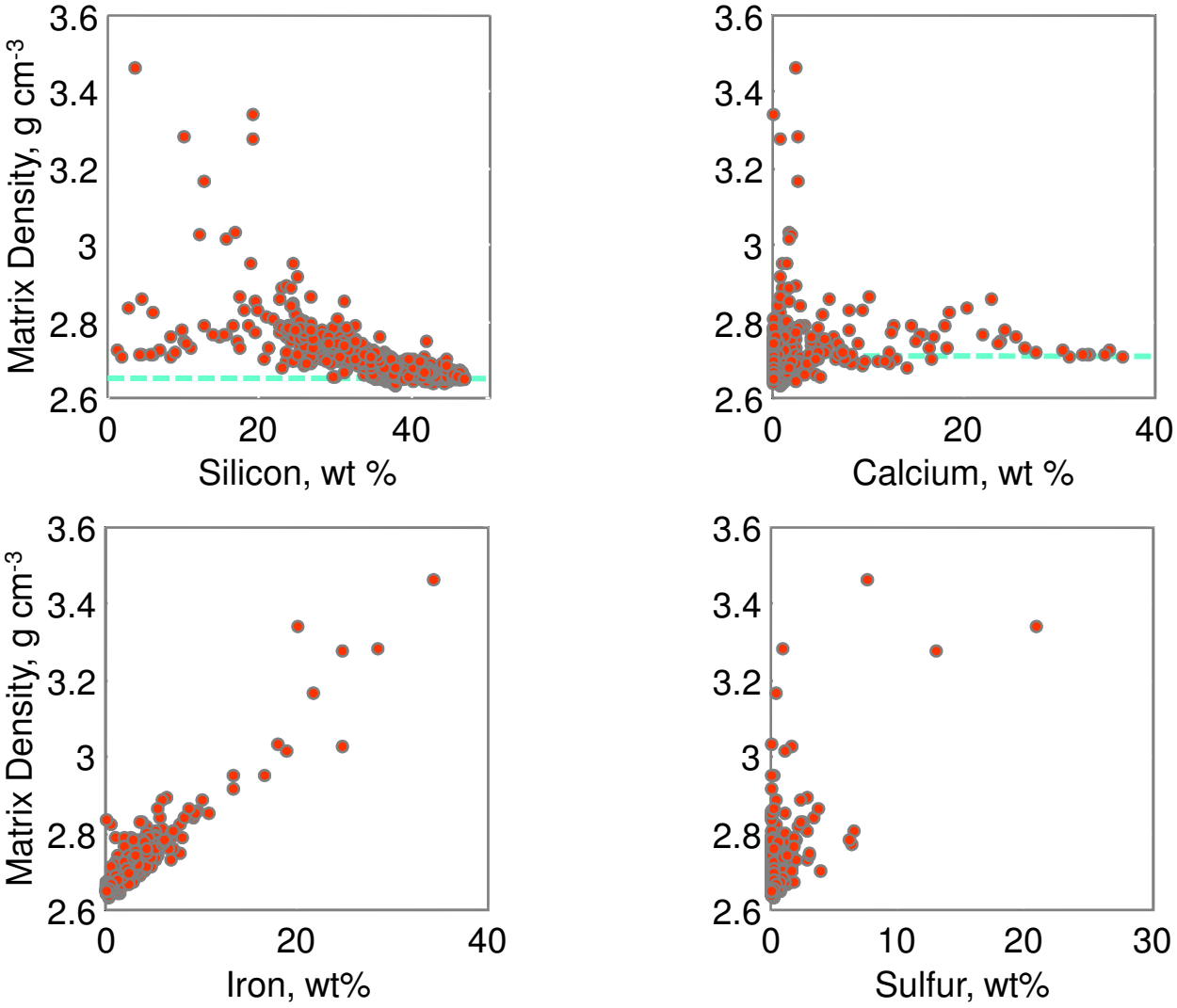
ρ_{ma} Increases with Iron



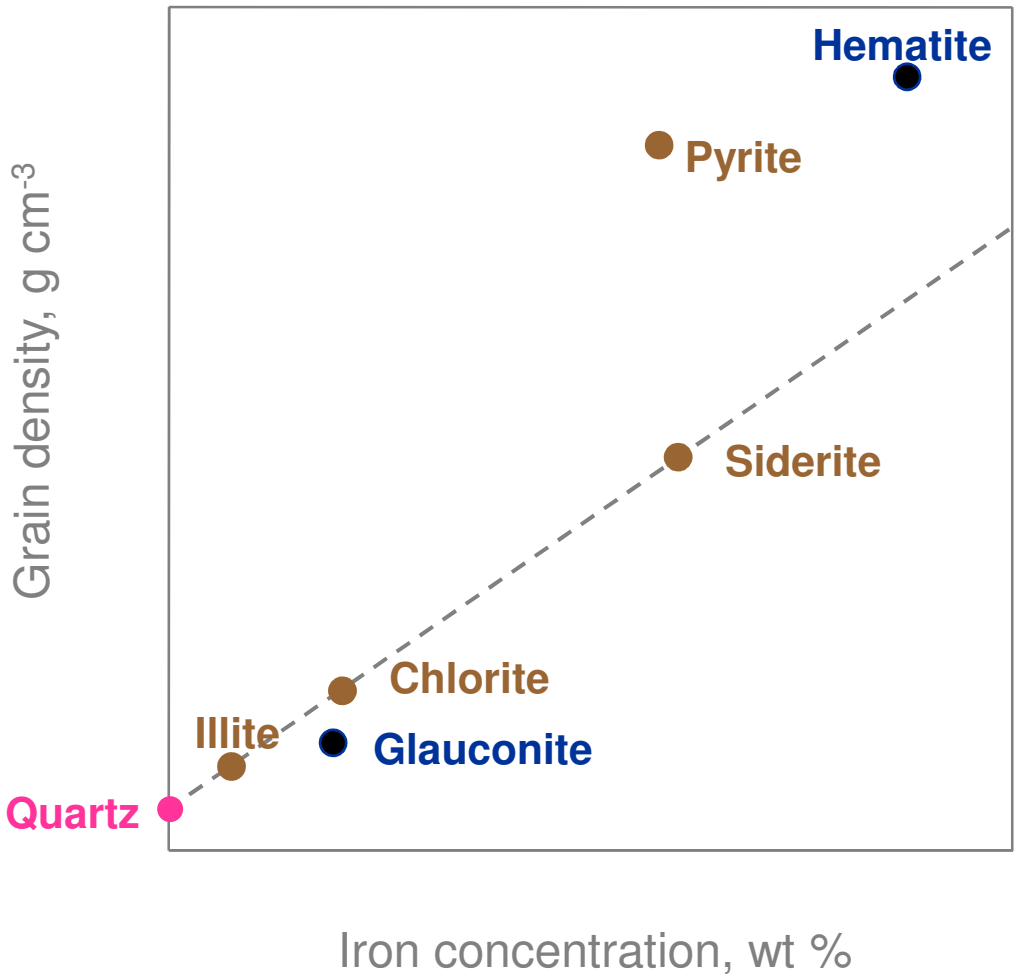




ρ_{ma} Also Increases with Sulfur



Density of Common Iron-bearing Minerals



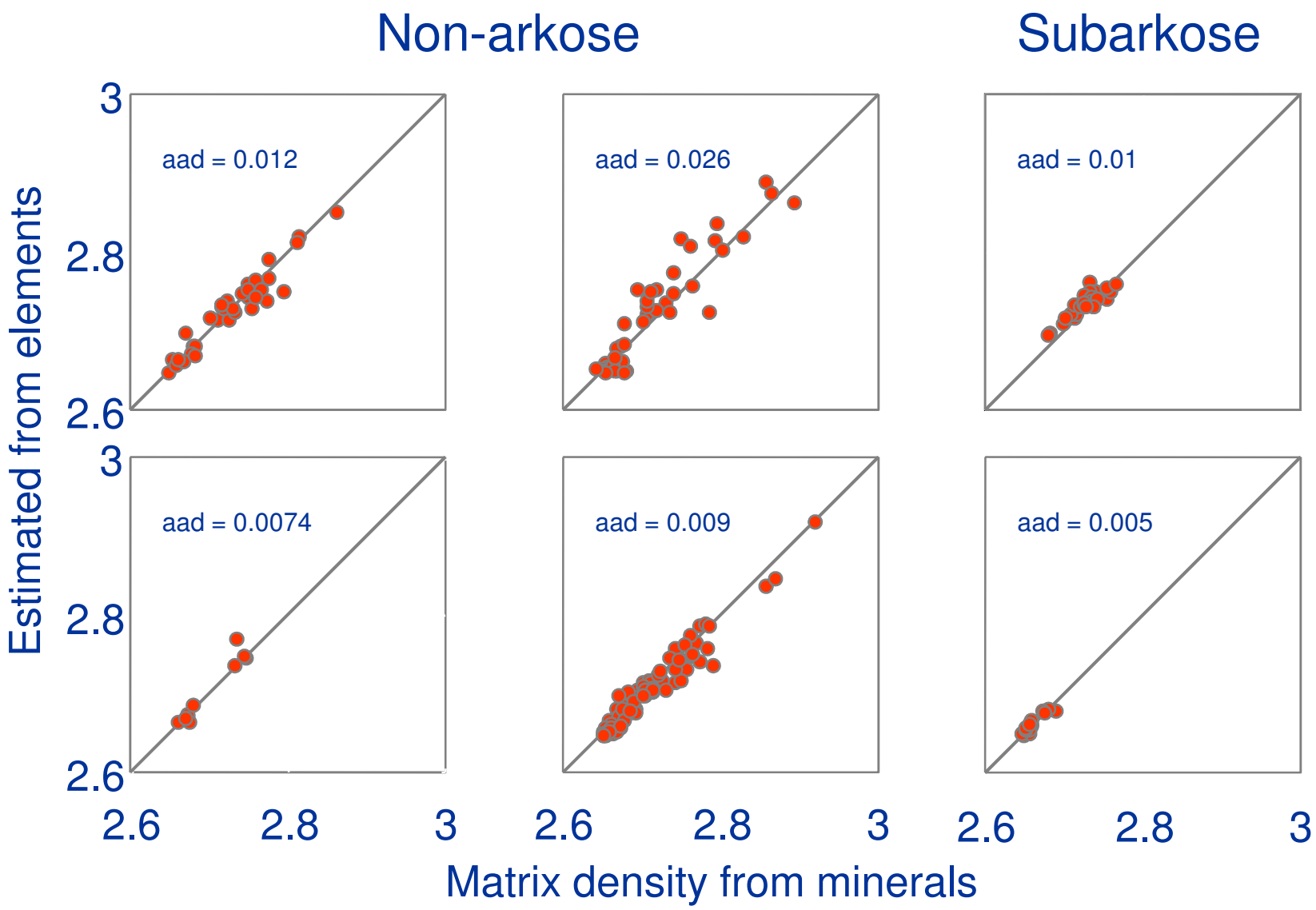
Regression Results

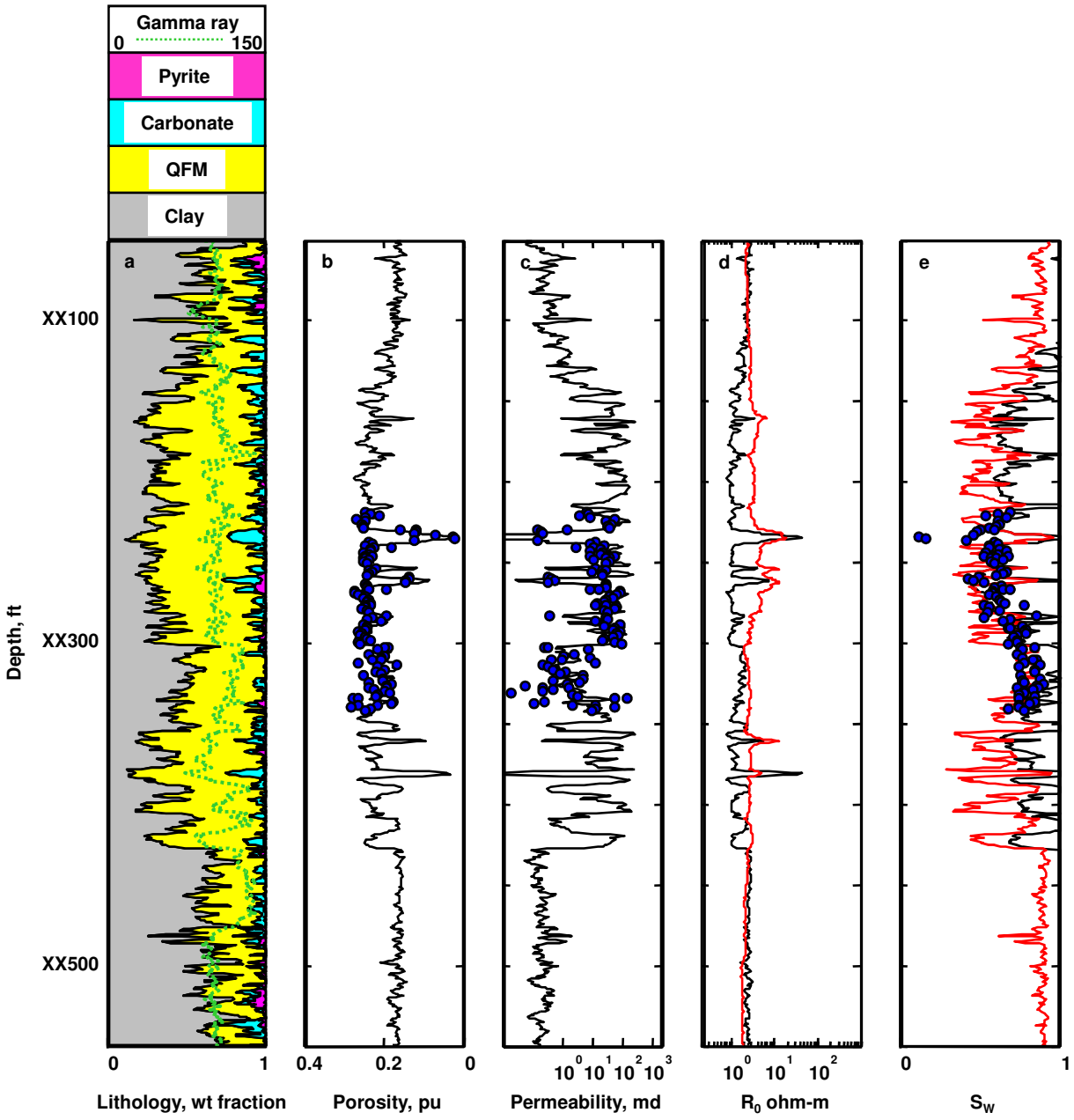
Non-arkose & Subarkose

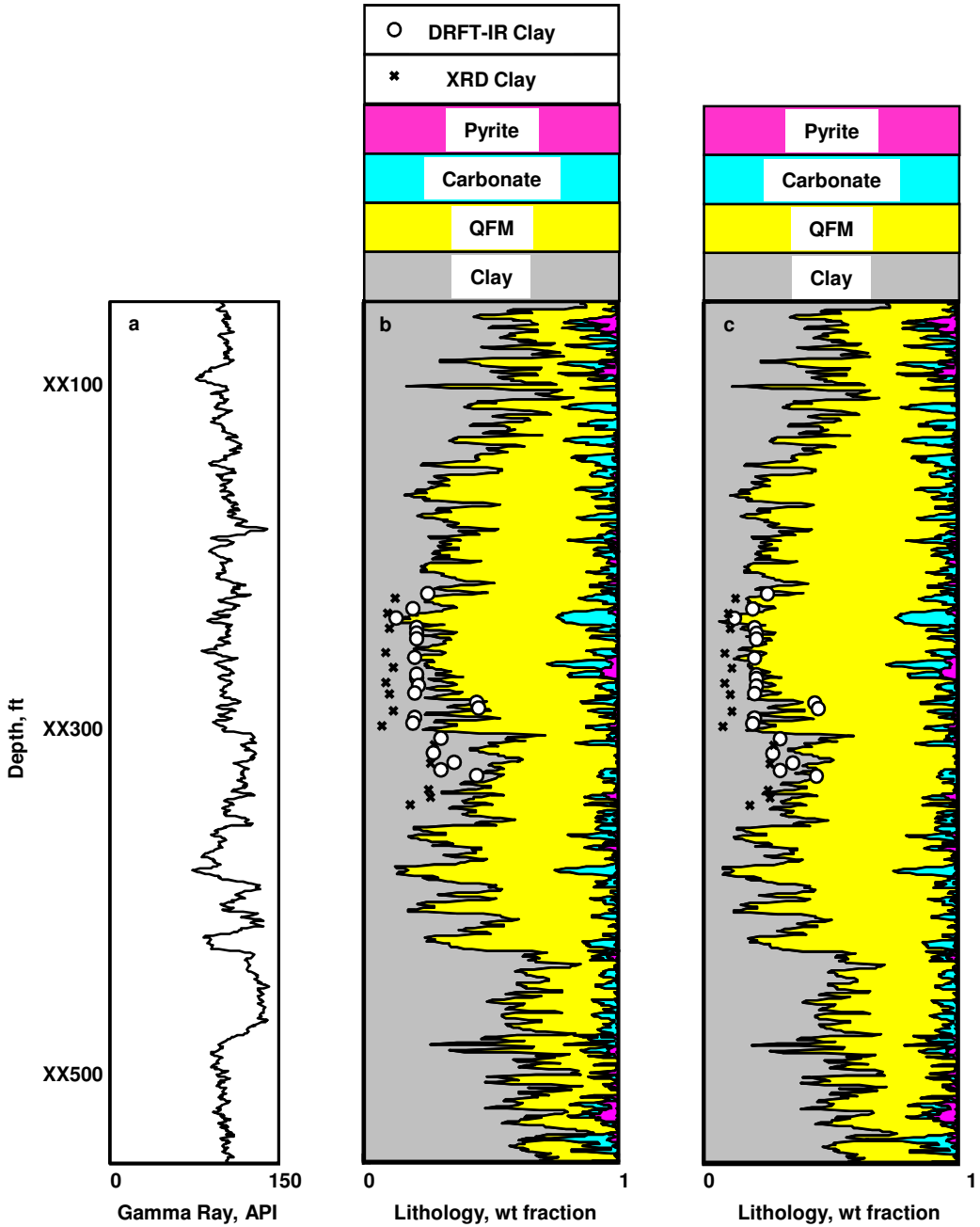
$$\rho_{ma} = 2.620 + 0.0490\,Si + 0.2274\,(Ca + 0.6\,Na) + 1.993\,(Fe + 0.14\,Al) + 1.193\,S$$

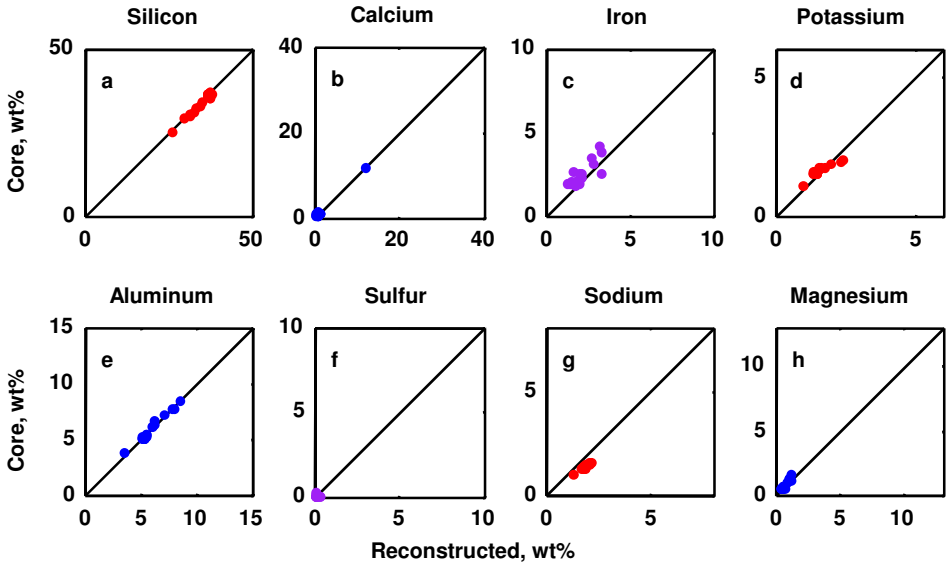
$r = 0.967$; std error 0.015 g cm^{-3}

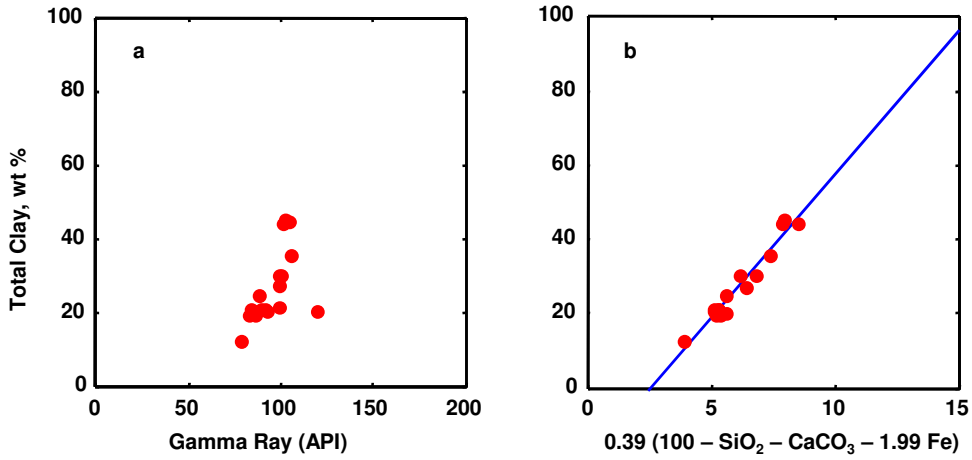
Measured vs Computed Density

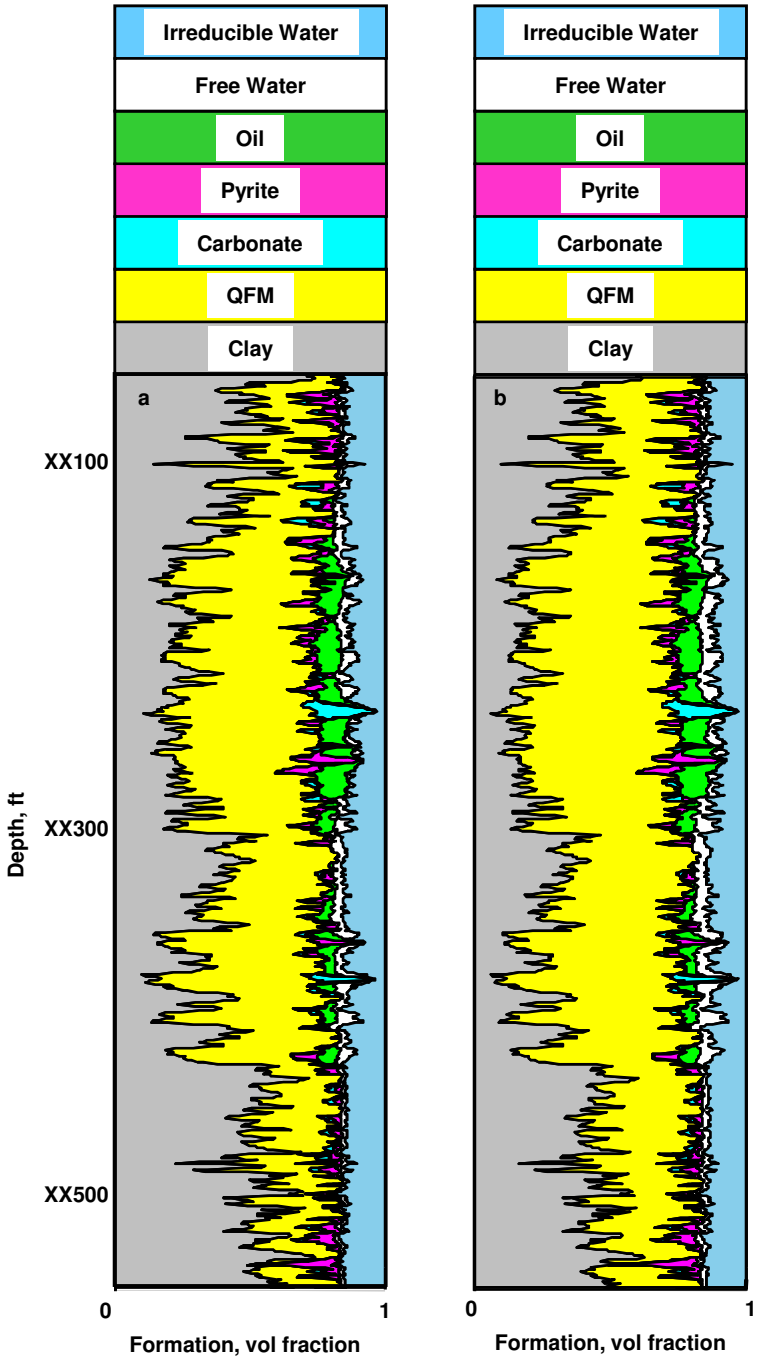



Gamma ray
0
150
Pyrite
Carbonate
QFM
Clay
a
b
c
d
e
XX100
XX300
XX500
Depth, ft
0
1
0.4
0.2
0
10^0 10^1 10^2 10^3
10^0 10^1 10^2
0
1
Lithology, wt fraction
Porosity, pu
Permeability, md
R_0 ohm-m
S_W

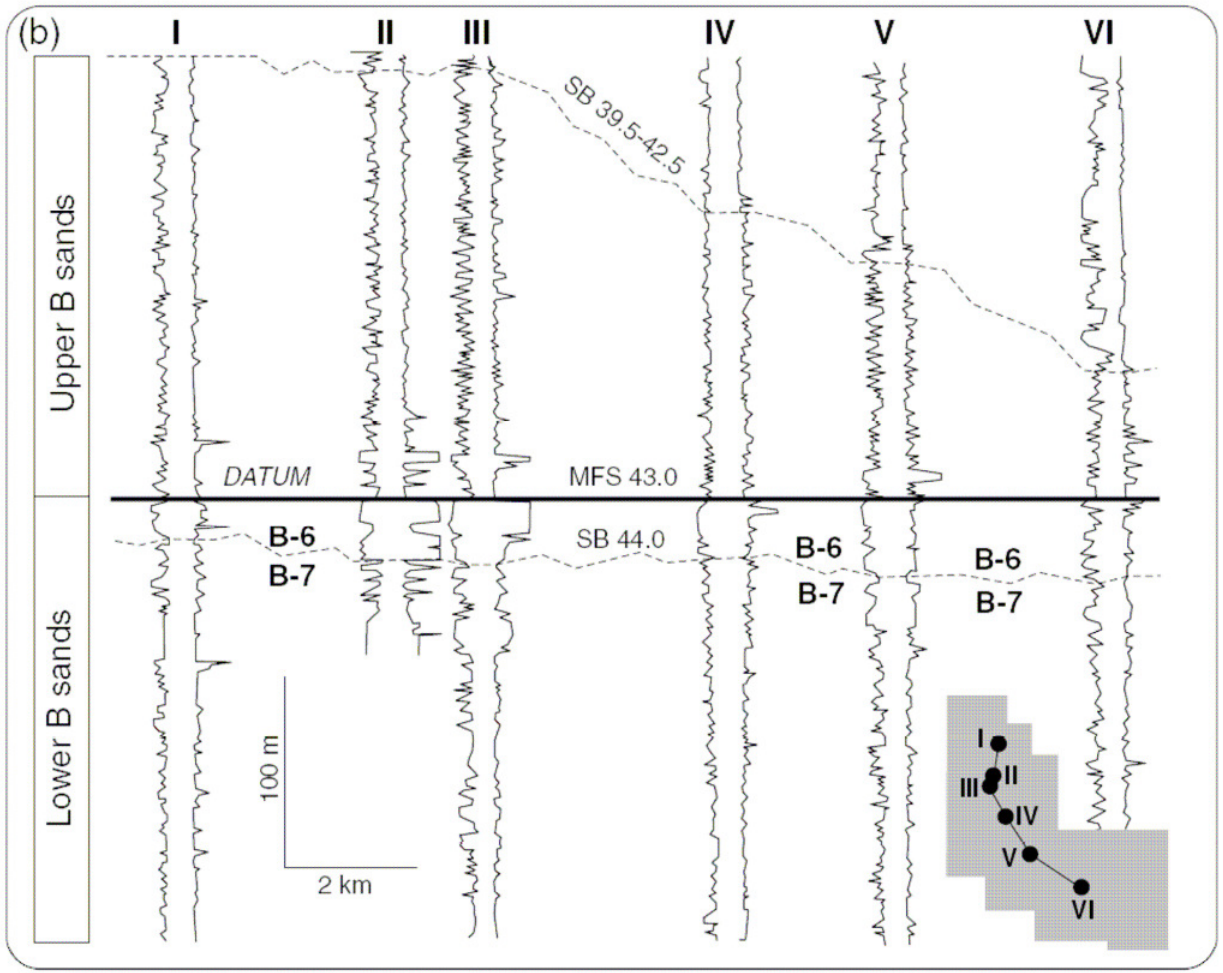

DRFT-IR Clay
XRD Clay
Pyrite
Carbonate
QFM
Clay
a
b
c
Depth, ft
XX100
XX300
XX500
0
150
Gamma Ray, API
0
1
Lithology, wt fraction
0
1
Lithology, wt fraction


Silicon
Calcium
Iron
Potassium
Aluminum
Sulfur
Sodium
Magnesium
a
b
c
d
e
f
g
h
Core, wt%
Core, wt%
Reconstructed, wt%
0
5
10
15
20
40
50


a
b
Total Clay, wt %
Gamma Ray (API)
0.39 (100 – SiO2 – CaCO3 – 1.99 Fe)
0
20
40
60
80
100
0
50
100
150
200
5
10
15

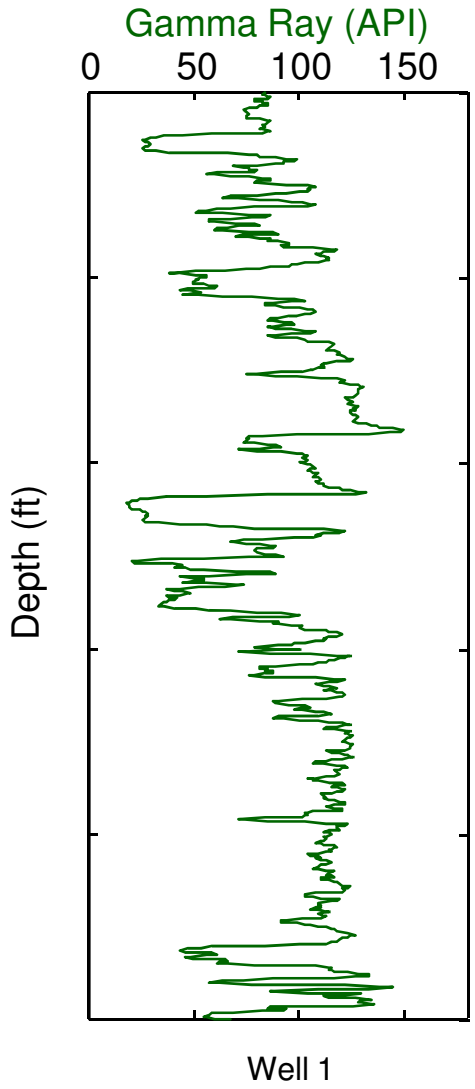

Irreducible Water
Free Water
Oil
Pyrite
Carbonate
QFM
Clay
a
b
XX100
XX300
XX500
Depth, ft
0
1
Formation, vol fraction
0
1
Formation, vol fraction

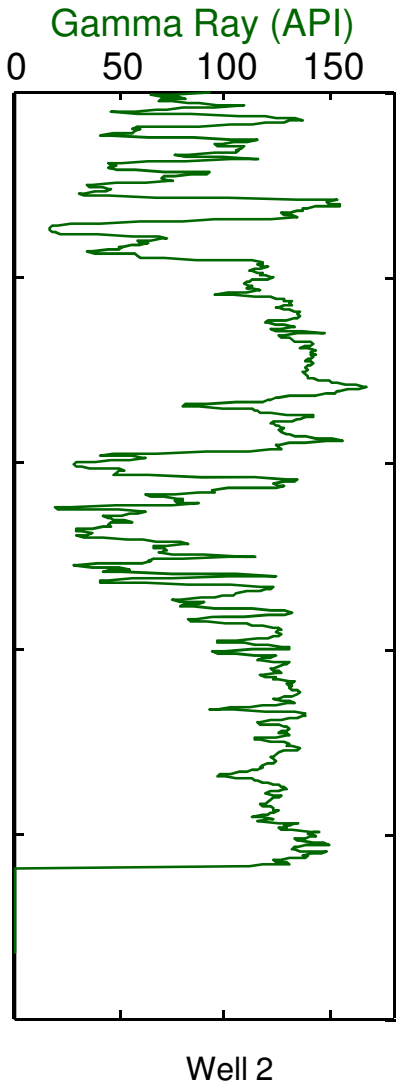
Well-to-Well Gamma Ray-Resistivity



Sometimes these
Correlations are
Difficult to understa
And not repeatable

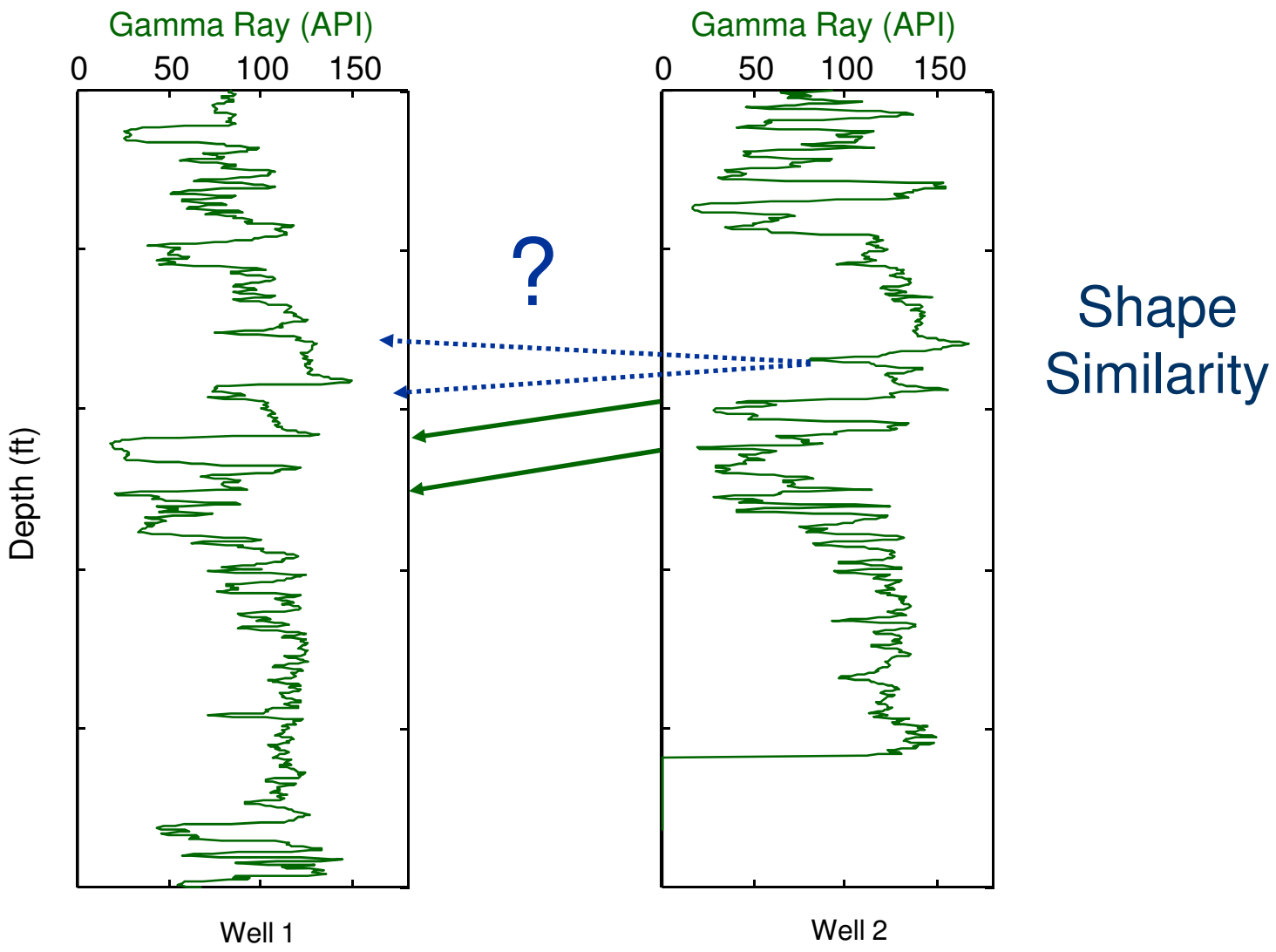
Ambiguous Correlations with Gamma Ray





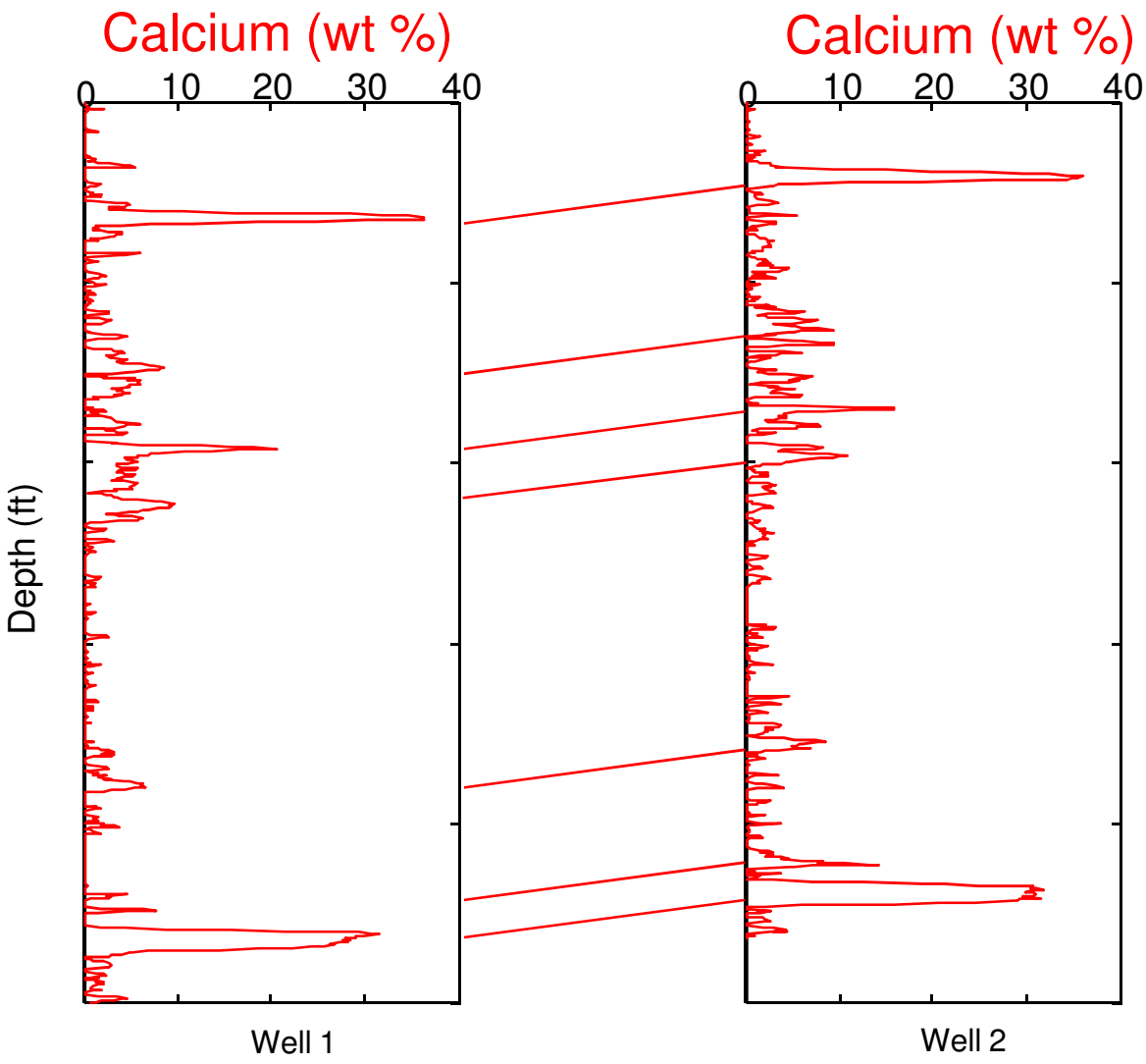
Shape Similarity

Ambiguous Correlations with Gamma Ray



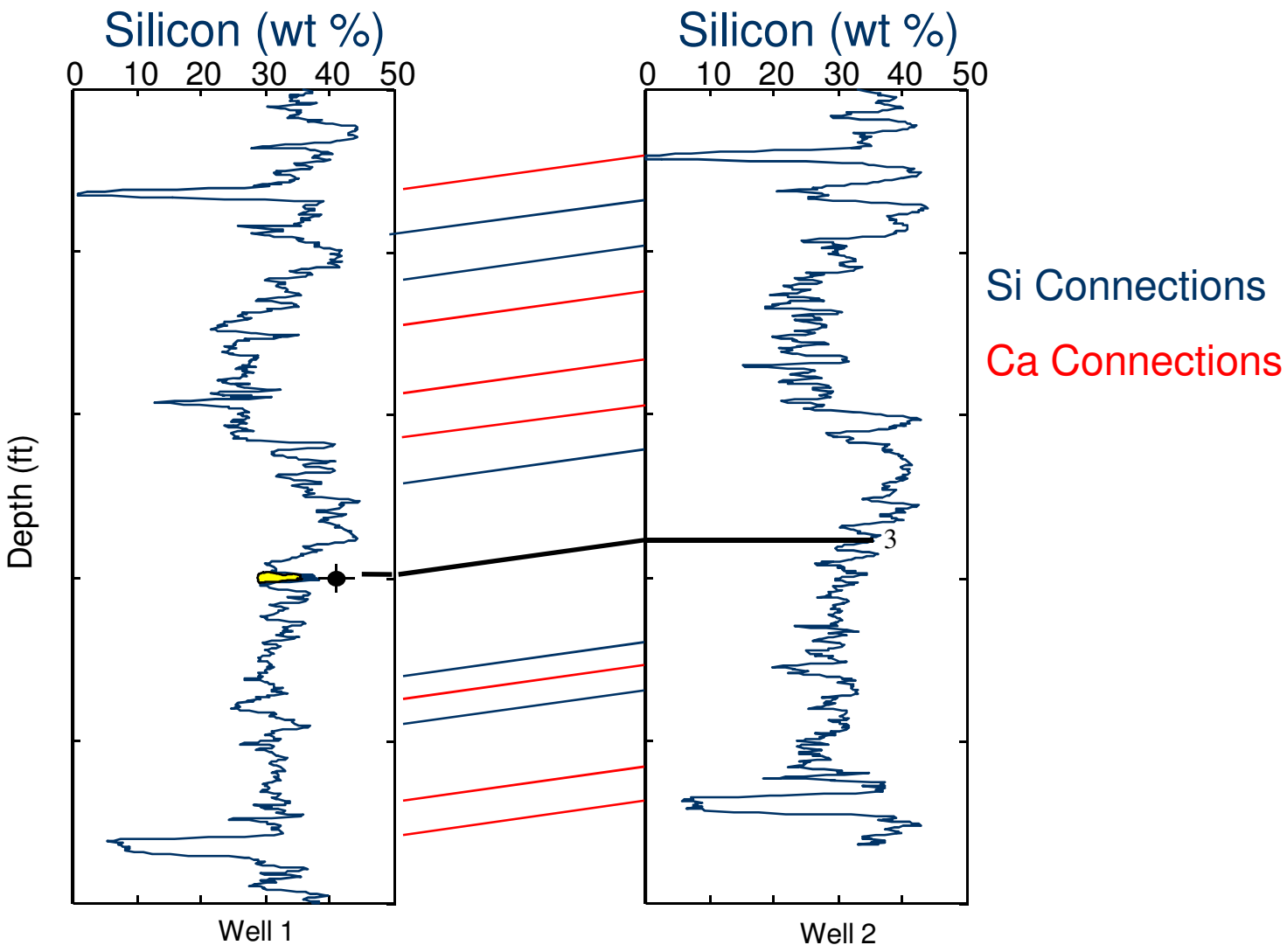
Shape Similarity

Chemostratigraphy Lowers Ambiguity



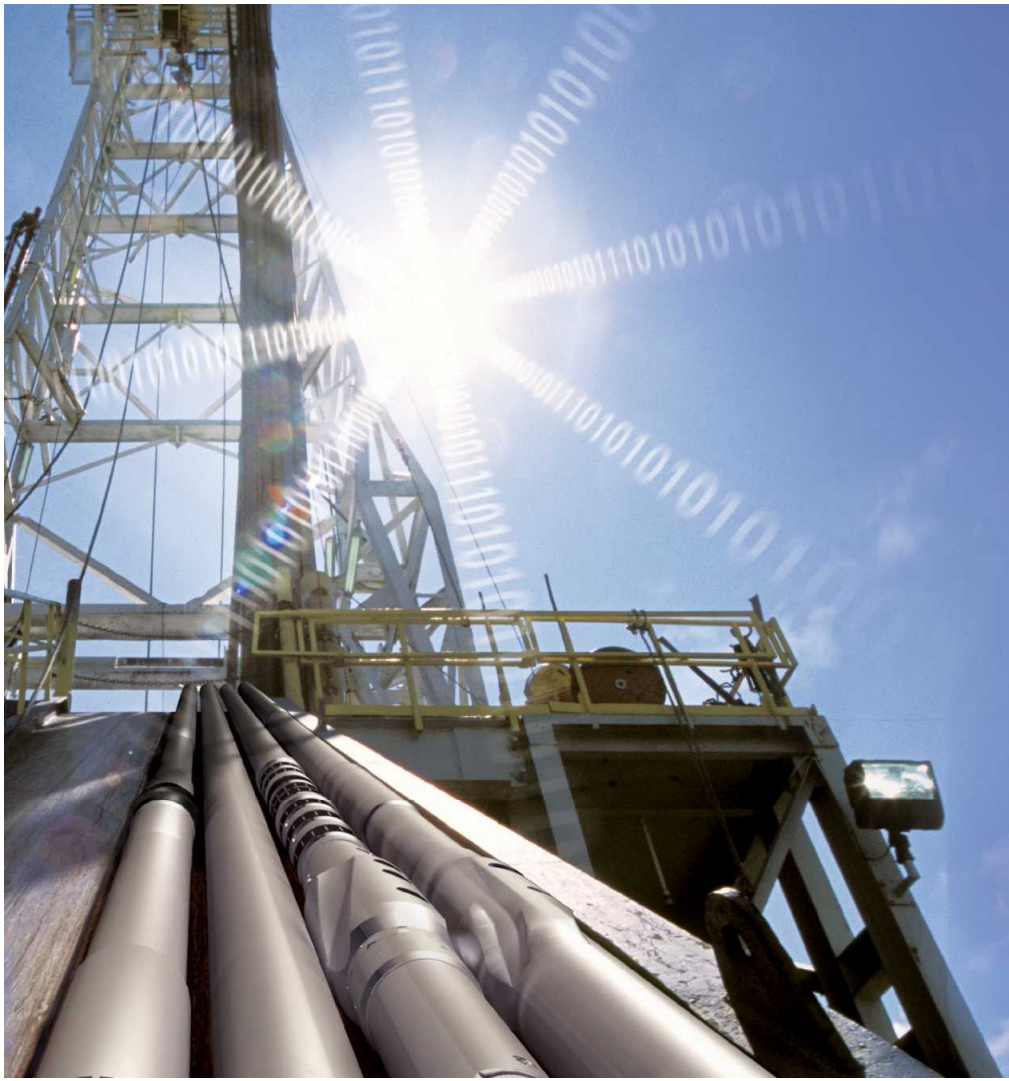
Shape Similarity & Absolute Value

This is the Chemostratigraphy Connection



Leaps of Science Follow New Analytical Capabilities

- Induced gamma ray spectroscopy is now becoming a standard oilfield service
- More data in an hour than in a lab geochemist's lifetime
- New elements are around the corner
- Challenge is on Academia and Industry to maximize use of these new data



Scope | The New Age of Drilling

These new-generation while-drilling services dramatically improve drilling performance and well placement—leading to increased production, sooner. Scope* services set new standards for reliability and data quality, while quadrupling the data rate over the industry standard of 3 bps.

EcoScope

EcoScope* logging while drilling. Delivering industry-first measurements, faster.

- Increases efficiency and safety by integrating drilling and formation evaluation sensors in one collar; eliminates one radioactive source
- Improves well placement with elemental capture, porosity, lithology, density, sigma, and resistivity measurements
- Improves drilling performance with measurements of annular pressure, borehole diameter, and downhole shock
- Logs at speeds of 450 ft/hr while recording 2 points/ft

StethoScope

StethoScope* formation pressure while drilling. Improving efficiency and reducing risk.

- Saves time by measuring reservoir pressure in less time than needed to make a connection
- Allows mud weight optimization to avoid kicks and drilling delays
- Eliminates need to orient the tool—even in vertical wells—by using a setting piston
- Improves measurement quality through Smart Pretest* system and pumps-off option

TeleScope

TeleScope* high-speed telemetry while drilling. Transmitting more data, faster.

- Improves efficiency by transmitting data at rotary steerable drilling speeds
- Delivers 4 times the data rate of the industry standard by using the Orion* telemetry protocol
- Improves well placement by providing comprehensive picture of downhole environment through real-time measurements from multiple tools
- Sets a new standard for data transmission

www.oilfield.slb.com/scope