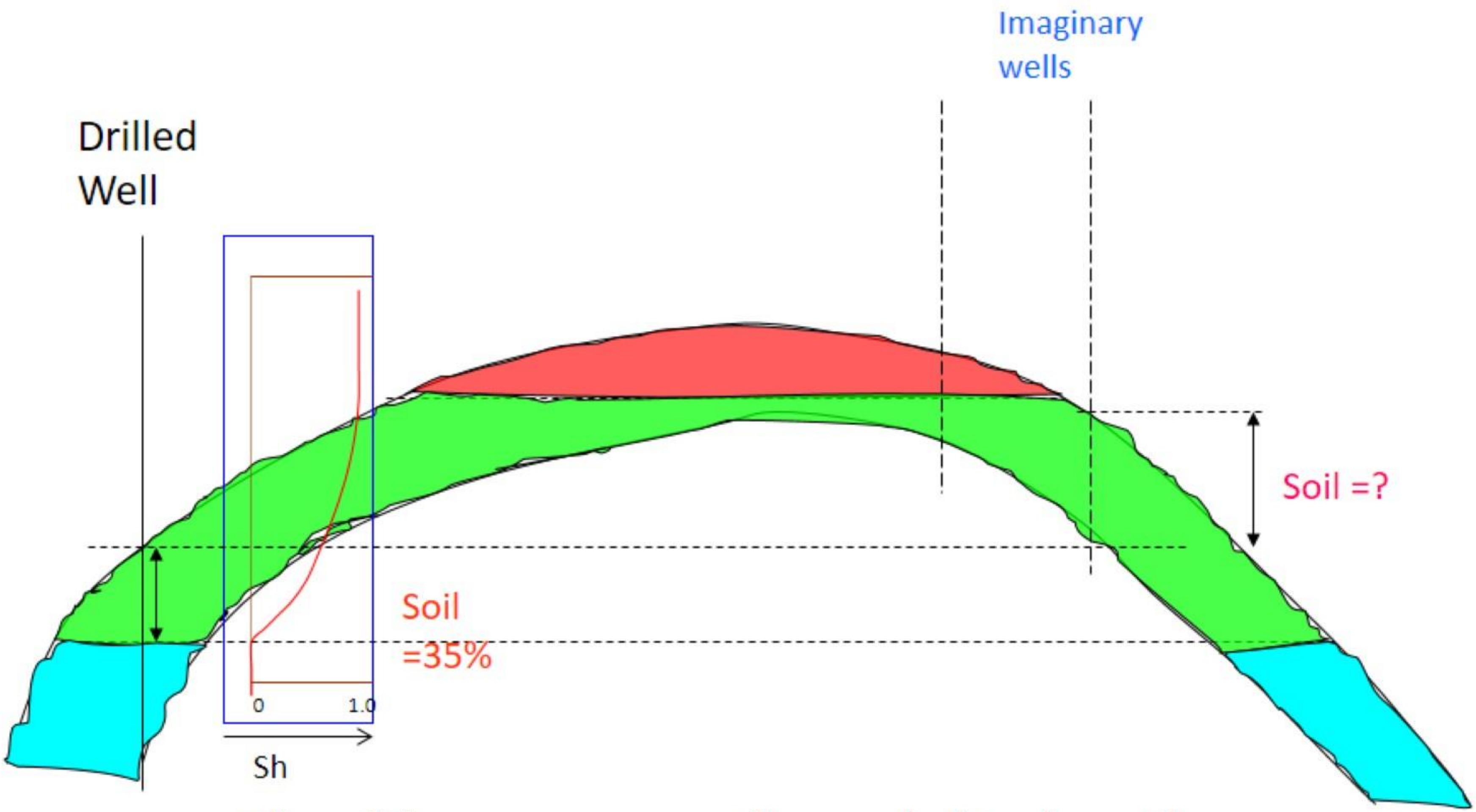
Saturation-Height Function

Leong Hoon Yoong

Saturation-Height Function

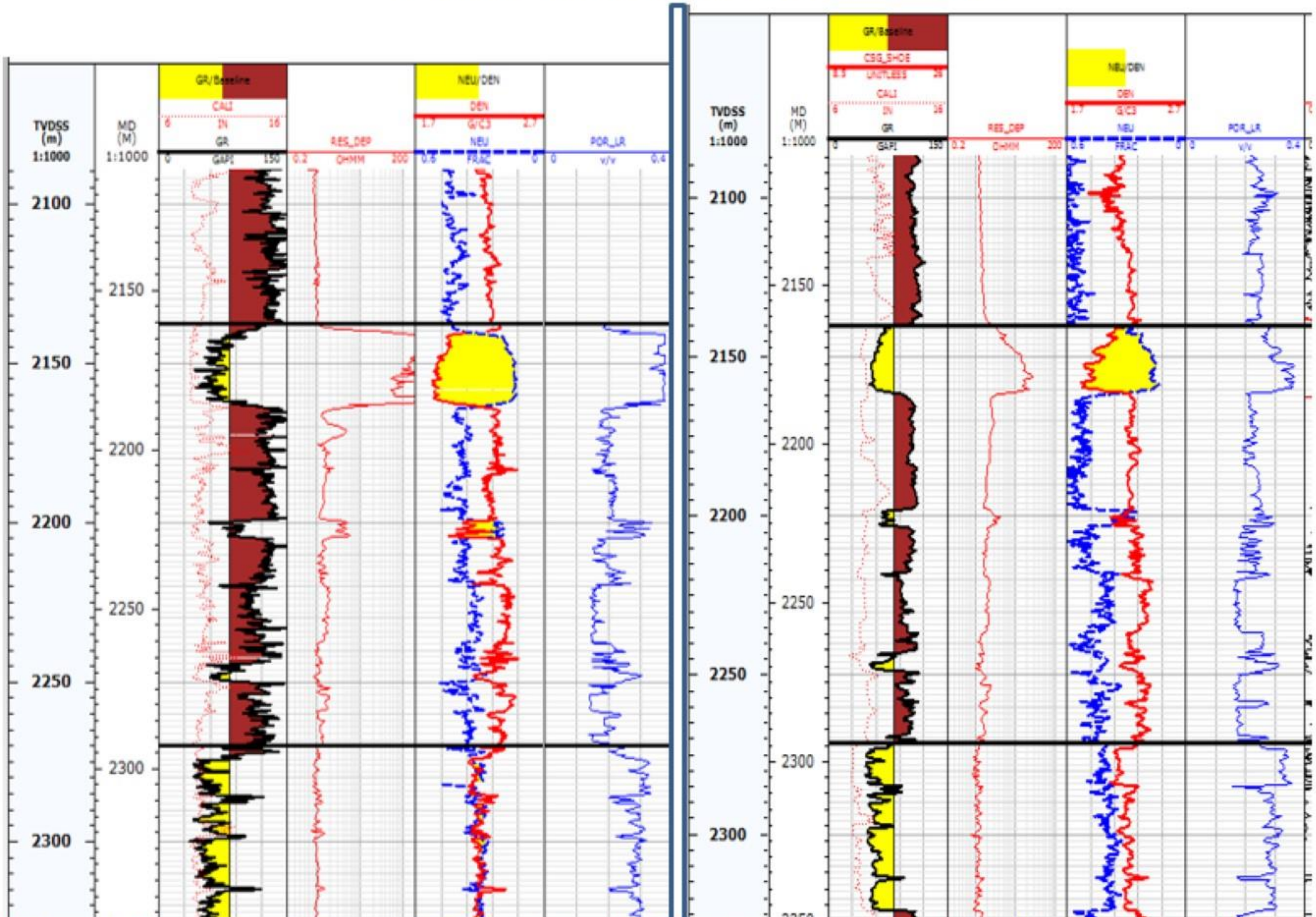
Why use saturation-Height Function?

Why not use log-derived saturation?



Should we use a well result (Sw) as the average Sw for the whole reservoir?

Filtrate Invasion



LWD resistivity in original hole reads 10 times higher than the wireline resistivity in the sidetracked well on the right due to invasion effect. gas saturation=91%PU for the original hole and 71%PU for the sidetrack hole.

Who use saturation-height function

- Geologist uses it to generate GIIP or OIIP in his static model
- The result of static model is passed to Reservoir Engineer for the starting point of his dynamic modelling (history matching).

Capillary pressure and Buoyancy force in hydrocarbon charge into the reservoir

Capillary force and capillary pressure

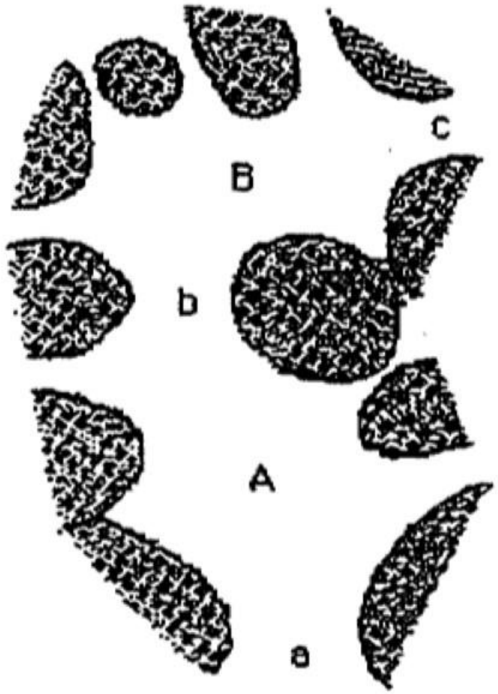


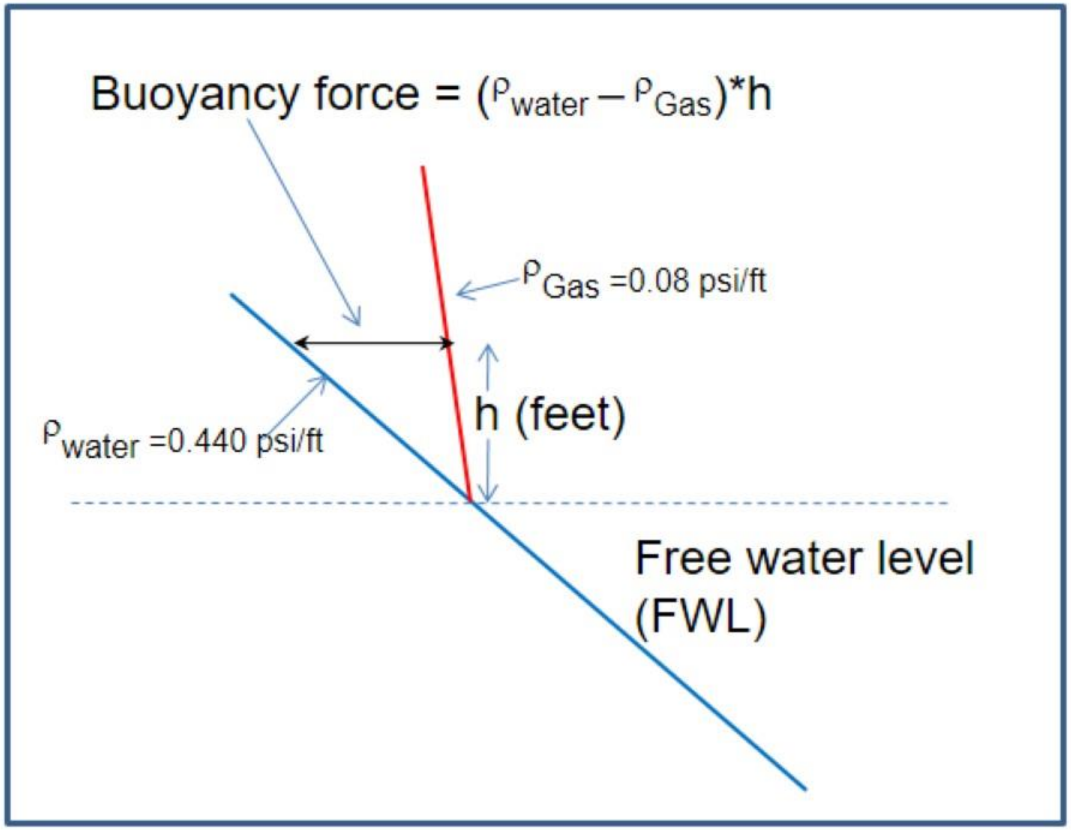
Figure . 1.
Cross section of a pore.
The water in the pore space is at a hydrostatic pressure. The larger pores (A and B) are connected by smaller diameter pore throats (a and b); pore throat c leads to the next pore.
As numerical values for parameters are easier to visualise, the pore throats are given realistic diameters which will be used in the examples:
a = 4 μm,
b = 3 μm,
c = 2 μm.

The capillary pressure holding the water in the pore = Pc

$Pc = 2\,\sigma Cos\theta/r$ ……………………………………………(1)

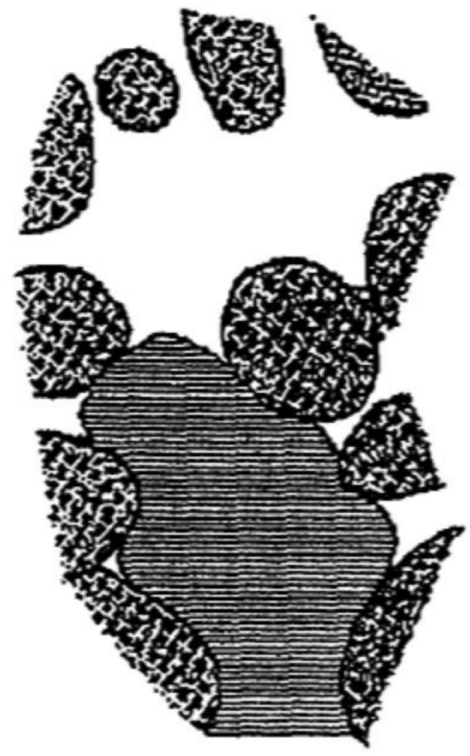
Where σ is the interfacial tension between gas or oil and water,
θ is the contact angle between the wetting phase (water) and the rock,
and r is the radius of the pore throat

Buoyancy force



Charging of reservoir

$\Delta\rho.g.h < 2\sigma \cos\theta/r$

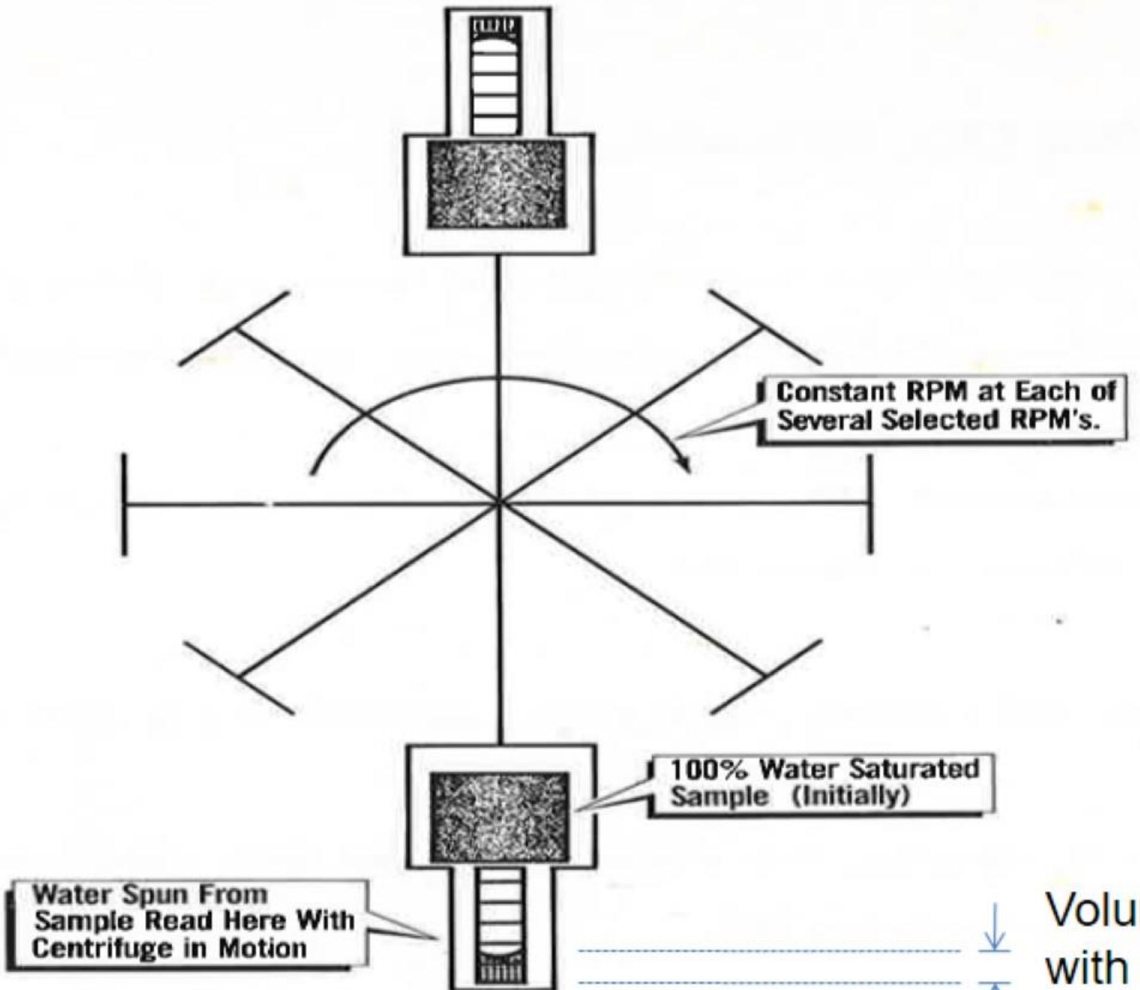


$\Delta\rho.g.h >= 2\sigma \cos\theta/r$

History repeated in the Laboratory

Capillary pressure test

Capillary Pressure Test



Centrifugal Apparatus (Drainage)

Acceleration = $r\omega 2$
Where r is the rotational radius, and ω is the angular velocity in revolution per minute

Volume of brine can be read with a stroboscope (using photo or the eye)

Typical Capillary Pressure Result

International Oil and Gas Company (IOGC) — Page : 4 - 1

Well : Well-4 — File : SCM00007

SUMMARY OF CAPILLARY PRESSURE RESULTS

Centrifuge Method - Ambient Condition

Fluid System : Air - Water (Drainage)
Test Method : High Speed Centrifuge
Conditions : Ambient

Sample ID	Depth ft	Net Overburden (800 psi) Klinkenberg Permeability md	Permeability to air (est.) md	Porosity %	0	1	2	5	10	25	50	100	200	350
		Pressure,		psi :	Inlet-Face Water Saturation, % Pore Volume									
196A	6812.6	685.	690.	22.6	100.0	68.2	49.8	33.5	25.3	18.1	14.5	12.1	10.5	9.6
91A	6693.0	332.	337.	22.0	100.0	87.3	71.7	35.6	27.1	21.7	18.8	16.5	14.5	12.8
75A	6675.5	50.	54.	21.3	100.0	85.5	73.8	56.0	42.9	28.5	20.8	16.2	13.5	11.9
89A	6690.8	211.	218.	21.2	100.0	94.2	73.6	43.3	29.4	23.2	20.9	19.2	17.4	15.0
93A	6695.1	297.	305.	20.9	100.0	76.1	54.2	35.0	25.8	18.3	15.0	12.5	10.3	7.7
105A	6708.3	90.6	95.4	20.1	100.0	100.0	81.6	53.6	41.2	31.1	26.2	22.9	20.6	19.3
23A	6618.2	4.7	5.8	19.5	100.0	100.0	100.0	95.9	82.9	55.2	45.1	37.4	32.9	31.3
248A	6870.3	109.1	114.3	19.1	100.0	92.1	68.2	47.0	36.4	26.9	22.1	18.7	16.3	14.9
242A	6864.0	44.0	48.2	19.0	100.0	81.8	68.6	48.3	35.3	24.4	19.9	17.2	15.6	14.8
157A	6768.6	18.6	21.0	18.3	100.0	100.0	97.6	81.4	66.6	47.9	38.3	33.0	29.8	28.1
123A	6731.3	63.5	67.5	17.8	100.0	99.9	89.0	56.7	41.7	33.6	29.2	25.7	23.1	21.3
132A	6741.1	33.9	37.2	16.8	100.0	100.0	93.6	65.5	51.0	37.4	29.8	24.0	19.5	16.8
319A	7448.7	24.2	26.8	16.4	100.0	100.0	94.3	69.1	53.9	39.3	31.8	26.2	21.9	18.3
322A	7452.3	27.81	30.60	16.4	100.0	100.0	88.1	68.1	53.8	41.2	34.3	28.6	23.8	20.5
171A	6783.8	5.37	6.41	16.1	100.0	100.0	100.0	80.8	64.7	49.0	40.5	34.4	30.4	28.3

Typical Interfacial Tension and contact angle constants

System	θ Contact Angle	Cosine Contact θ	T Interfacial Tension	T Cosine θ
Laboratory				
Air-water	0	1.0	72	72
Oil-water	30	0.866	48	42
Air-mercury	140	0.765	480	367
Air-oil	0	1.0	24	24
Reservoir				
Water-oil	30	0.866	30	26
Water-gas	0	1.0	50*	50

*Pressure and temperature dependent. Reasonable value to depth of 5000 feet.

"normalized" Capillary pressure, PC_IFT

- $$\frac{\mathbf{PC}_{\mathbf{A\text{-}Hg}}}{(\mathbf{Tcos}\theta)_{\mathbf{A\text{-}Hg}}} = \frac{\mathbf{PC}_{\mathbf{A\text{-}B}}}{(\mathbf{Tcos}\theta)_{A\text{-}B}} = \text{Constant}$$

- PC_IFT= $(\mathbf{PC}_{\mathbf{system\ x}}) / (\mathbf{Tcos}\theta)_{\mathbf{system\ x}}$

Conversion of Air-Mercury (A-Hg) Capillary Pressure Data to Air-Brine (A-B) Data

- $PC_{A\text{-}Hg} = PC_{A\text{-}B} * (T\cos\theta)_{A\text{-}Hg} / (T\cos\theta)_{A\text{-}B}$

  $= PC_{A\text{-}B} * 367/72$

  $= 5.1 * PC_{A\text{-}B}$

Leverett-J function & RQI

$$J = \frac{P_c}{\sigma \cdot \cos\theta} \cdot \sqrt{\frac{k}{\phi}}$$

J=0.2166*Pc*SQRT(k/ϕ)
Pc in psi, k in mD and ϕ in fraction

$$RQI = 0.0314 \sqrt{\frac{k}{\phi}}$$

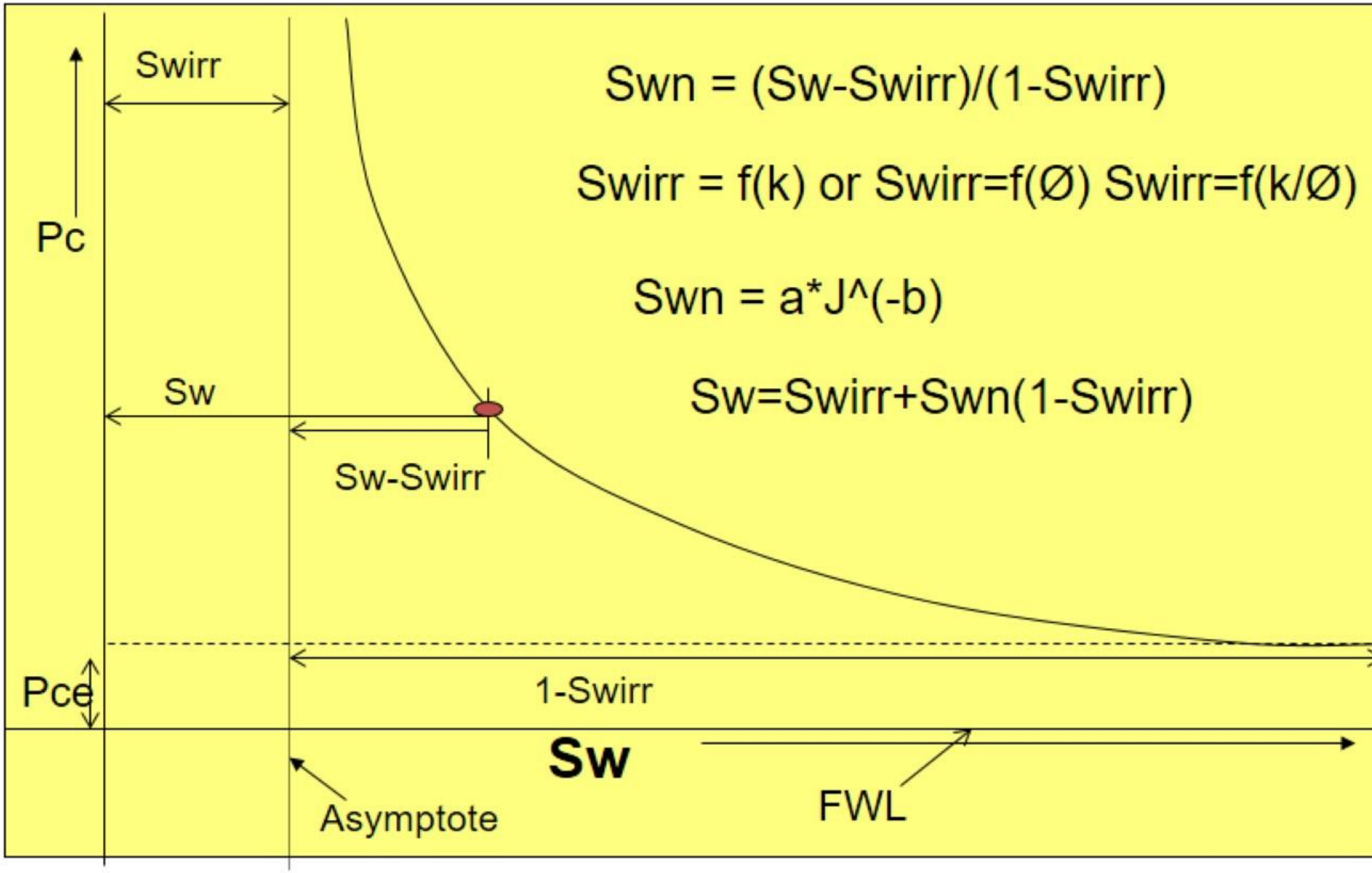
$\sigma \cos\phi$=72 dynes/cm

		Pressure,		psi :	0	1	2	5	10	25	50	100	200	350		
		Net Overburden (800 psi)														
Sample	Depth	Klinkenberg	ermeability		Leverett-J											
ID		Permeability	o air (est.	Porosity												
	m	md	md	%	% Pore Volume										SQRT(k/Phi)	RQI
196A	2076.47	685.	690.	22.6											55.06	1.73
91A	2040.02	332.	337.	22.0											38.82	1.22
75A	2034.68	49.8	54.4	21.3											15.29	0.48
89A	2039.36	211.	218.	21.2											31.56	0.99
93A	2040.68	297.	305.	20.9											37.73	1.18
105A	2044.70	90.6	95.4	20.1											21.23	0.67
23A	2017.24	4.70	5.80	19.5											4.91	0.15
248A	2094.07	109.	114.	19.1											23.90	0.75
242A	2092.16	44.0	48.2	19.0											15.22	0.48
157A	2063.06	18.6	21.0	18.3											10.08	0.32
123A	2051.71	63.5	67.5	17.8											18.89	0.59
132A	2054.70	33.9	37.2	16.8											14.20	0.45
319A	2270.35	24.2	26.8	16.4											12.14	0.38
322A	2271.45	27.8	30.6	16.4											13.02	0.41
171A	2067.69	5.37	6.41	16.1											5.78	0.18

Calculated J values

		Pressure,		psi :	0	1	2	5	10	25	50	100	200	350		
				HAFWL:		2.91545	5.8309	14.5773	29.1545	72.8863	145.773	291.5451895	583.09	1020.40816		
		Net Overburden (800 psi)														
Sample	Depth	Klinkenbergermeability			Leverette J											
ID		Permeability	o air (est.	Porosity												
	m	md	md	frac											SQRT(k/Phi)	RQI
196A	2076.47	685.	690.	0.226	0.000	0.166	0.331	0.828	1.656	4.141	8.282	16.565	33.129	57.977	55.063	1.729
91A	2040.02	332.	337.	0.220	0.000	0.117	0.234	0.584	1.168	2.920	5.840	11.679	23.358	40.877	38.823	1.219
75A	2034.68	49.8	54.4	0.213	0.000	0.046	0.092	0.230	0.460	1.150	2.300	4.599	9.198	16.097	15.288	0.480
89A	2039.36	211.	218.	0.212	0.000	0.095	0.190	0.475	0.950	2.374	4.748	9.496	18.991	33.235	31.564	0.991
93A	2040.68	297.	305.	0.209	0.000	0.113	0.227	0.567	1.135	2.837	5.675	11.349	22.698	39.722	37.725	1.185
105A	2044.70	90.6	95.4	0.201	0.000	0.064	0.128	0.319	0.639	1.597	3.194	6.388	12.776	22.358	21.235	0.667
23A	2017.24	4.70	5.80	0.195	0.000	0.015	0.030	0.074	0.148	0.369	0.739	1.477	2.955	5.171	4.911	0.154
248A	2094.07	109.	114.	0.191	0.000	0.072	0.144	0.359	0.719	1.797	3.594	7.189	14.377	25.160	23.896	0.750
242A	2092.16	44.0	48.2	0.190	0.000	0.046	0.092	0.229	0.458	1.144	2.289	4.578	9.155	16.022	15.217	0.478
157A	2063.06	18.6	21.0	0.183	0.000	0.030	0.061	0.152	0.303	0.758	1.516	3.033	6.065	10.614	10.081	0.317
123A	2051.71	63.5	67.5	0.178	0.000	0.057	0.114	0.284	0.568	1.421	2.842	5.684	11.367	19.893	18.893	0.593
132A	2054.70	33.9	37.2	0.168	0.000	0.043	0.085	0.214	0.427	1.068	2.136	4.271	8.542	14.949	14.198	0.446
171A	2067.69	5.4	6.4	0.161	0.000	0.017	0.035	0.087	0.174	0.435	0.869	1.738	3.476	6.083	5.778	0.181
319A	2270.35	24.2	26.8	0.164	0.000	0.037	0.073	0.183	0.365	0.913	1.826	3.652	7.305	12.784	12.141	0.381
322A	2271.45	27.8	30.6	0.164	0.000	0.039	0.078	0.196	0.392	0.979	1.959	3.917	7.835	13.711	13.022	0.409

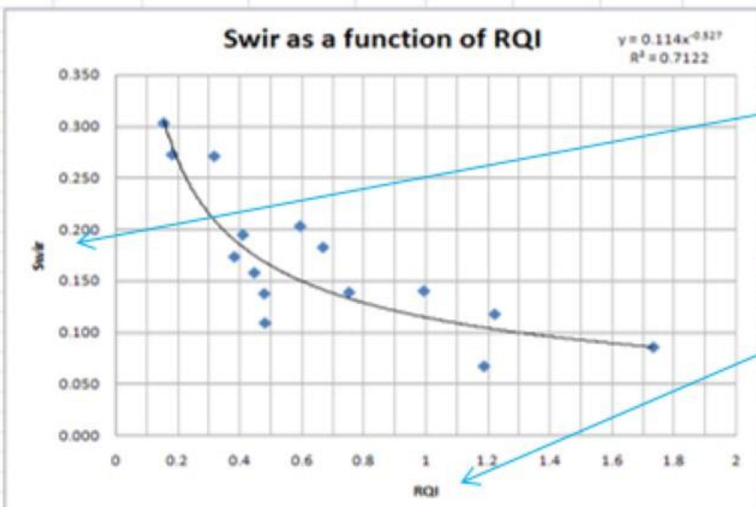
Brooks and Corey Method

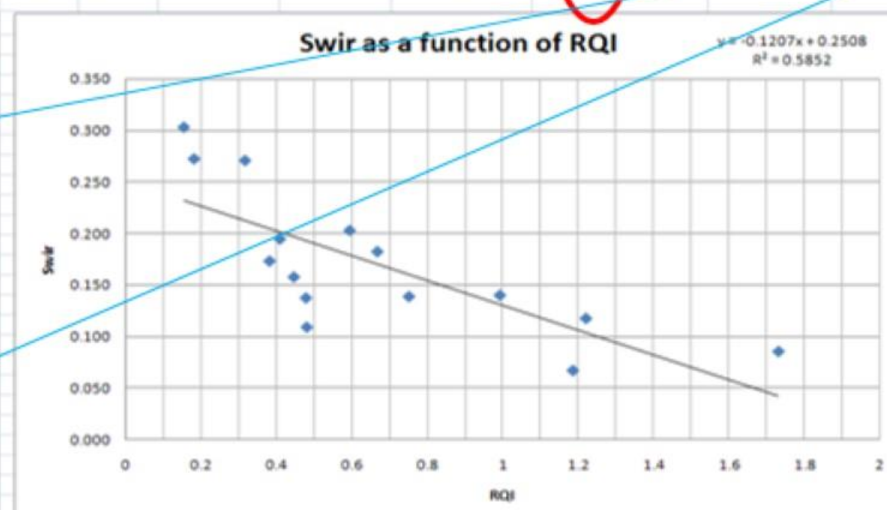


Swirr

Sw at 350 psi -0.01

Sample ID	Depth (m)	Net Overburden (800 psi): Klinkenberg Permeability (md)	Net Overburden (800 psi): Permeability to air (est.) (md)	Net Overburden (800 psi): Porosity (frac)	Inlet-Face Water Saturation, Pore Volume, frac — Pressure, psi: 0	1	2	5	10	25	50	100	200	350	Swir_trial	SQRT(k/Phi)	RQI
196A	2076.47	685.	690.	0.226	1.000	0.682	0.498	0.335	0.253	0.181	0.145	0.121	0.105	0.096	0.086	55.063	1.728971
91A	2040.02	332.	337.	0.220	1.000	0.873	0.717	0.356	0.271	0.217	0.188	0.165	0.145	0.128	0.118	38.823	1.219032
93A	2040.68	297.	305.	0.209	1.000	0.761	0.542	0.350	0.258	0.183	0.150	0.125	0.103	0.077	0.067	37.725	1.184572
89A	2039.36	211.	218.	0.212	1.000	0.942	0.736	0.433	0.294	0.232	0.209	0.192	0.174	0.150	0.140	31.564	0.991119
248A	2094.07	109.	114.	0.191	1.000	0.921	0.682	0.470	0.364	0.269	0.221	0.187	0.163	0.149	0.139	23.896	0.75033
105A	2044.70	90.6	95.4	0.201	1.000	1.000	0.816	0.536	0.412	0.311	0.262	0.229	0.206	0.193	0.183	21.235	0.666768
123A	2051.71	63.5	67.5	0.178	1.000	0.999	0.890	0.567	0.417	0.336	0.292	0.257	0.231	0.213	0.203	18.893	0.593239
75A	2034.68	49.8	54.4	0.213	1.000	0.855	0.738	0.560	0.429	0.285	0.208	0.162	0.135	0.119	0.109	15.288	0.480052
242A	2092.16	44.0	48.2	0.190	1.000	0.818	0.686	0.483	0.353	0.244	0.199	0.172	0.156	0.148	0.138	15.217	0.477804
132A	2054.70	33.9	37.2	0.168	1.000	1.000	0.936	0.655	0.510	0.374	0.298	0.240	0.195	0.168	0.158	14.198	0.445815
322A	2271.45	27.8	30.6	0.164	1.000	1.000	0.881	0.681	0.538	0.412	0.343	0.286	0.238	0.205	0.195	13.022	0.408879
319A	2270.35	24.2	26.8	0.164	1.000	1.000	0.943	0.691	0.539	0.393	0.318	0.262	0.219	0.183	0.173	12.141	0.381229
157A	2063.06	18.6	21.0	0.183	1.000	1.000	0.976	0.814	0.666	0.479	0.383	0.330	0.298	0.281	0.271	10.081	0.316543
171A	2067.69	5.37	6.41	0.161	1.000	1.000	1.000	0.808	0.647	0.490	0.405	0.344	0.304	0.283	0.273	5.778	0.181416
23A	2017.24	4.70	5.80	0.195	1.000	1.000	1.000	0.959	0.829	0.552	0.451	0.374	0.329	0.313	0.303	4.911	0.154202





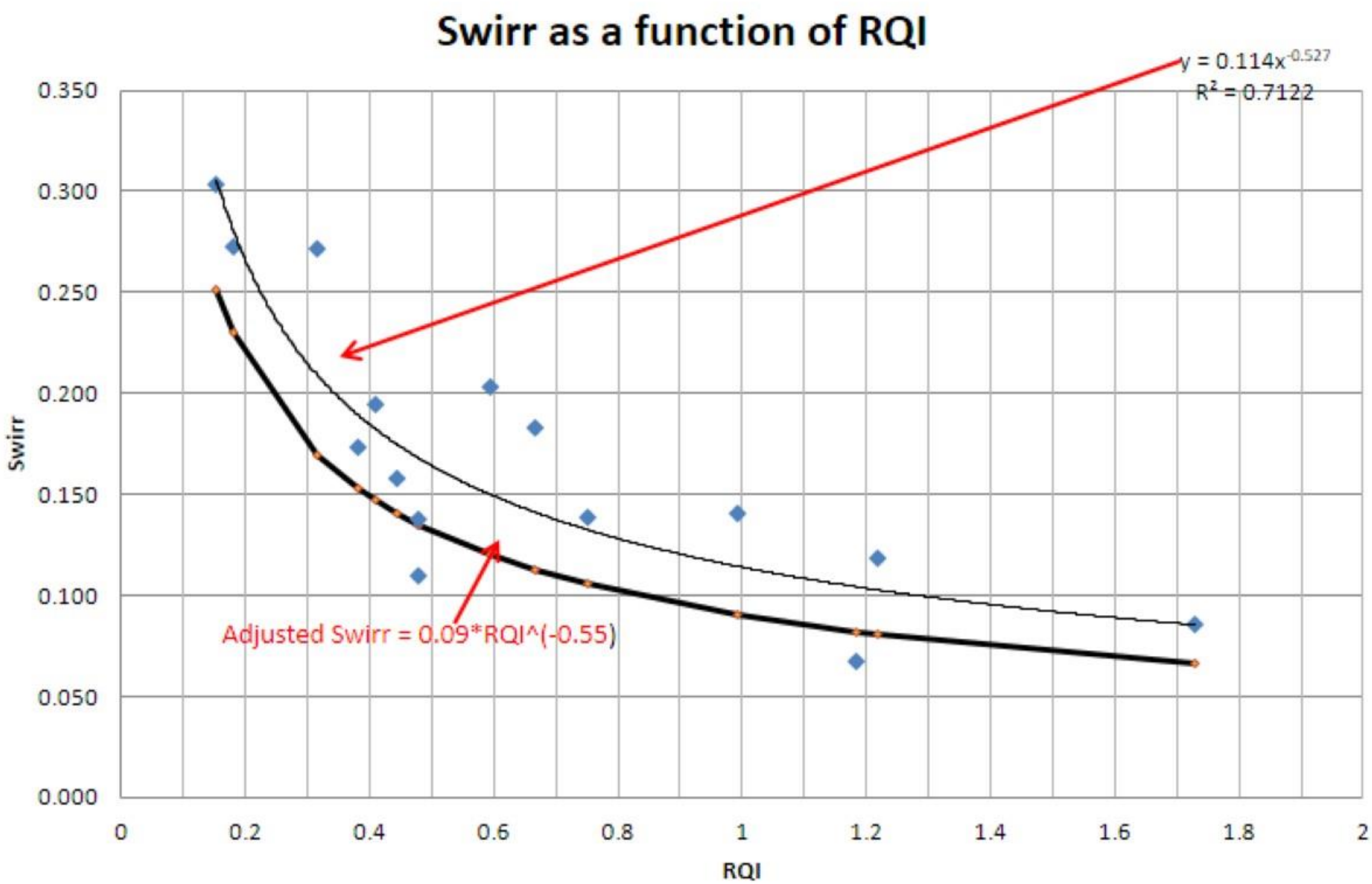
Swn

1. Swirr = 0.114*RQI^(-0.527)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
9																				
10		All data		Pressure,		psi :	0	1	2	5	10	25	50	100	200	350				
11						HAFWL:		2.9	5.8	14.6	29.2	72.9	145.8	291.5	583.1	1020.4		ft		
12				Net Overburden (800 psi)																
13		Sample	Depth	Klinkenberg	Permeability						Swn=Sw-Swir							Sqrt(k/Por)	RQI	
14		ID		Permeability	to air (est.)	Porosity											Swir			Swir_regression
15			m	md	md	frac					frac Pore Volume									
16																				
17		196A	2076.47	685.	690.	0.226	0.907	0.588	0.498	0.335	-0.039	0.181	-0.053	-0.375	-4.717	2.619	0.086	55.1	1.729	0.0854
18		91A	2040.02	332.	337.	0.220	0.886	0.758	0.717	0.356	-0.011	0.217	0.056	-0.140	-1.259	7.083	0.118	38.8	1.219	0.1027
19		75A	2034.68	49.8	54.4	0.213	0.798	0.562	0.542	0.350	-0.013	0.183	0.101	0.024	-0.196	-0.774	0.109	15.3	0.480	0.1678
20		89A	2039.36	211.	218.	0.212	0.871	0.813	0.736	0.433	0.025	0.232	0.104	-0.043	-0.730	-18.675	0.140	31.6	0.991	0.1145
21		93A	2040.68	297.	305.	0.209	0.884	0.805	0.682	0.470	0.099	0.269	0.093	-0.106	-1.149	8.562	0.067	37.7	1.185	0.1043
22		105A	2044.70	90.6	95.4	0.201	0.836	0.837	0.816	0.536	0.161	0.311	0.194	0.083	-0.263	-1.576	0.183	21.2	0.667	0.1411
23		23A	2017.24	4.70	5.80	0.195	0.560	0.573	0.890	0.567	0.175	0.336	0.277	0.227	0.151	0.040	0.303	4.9	0.154	0.3053
24		248A	2094.07	109.	114.	0.191	0.847	0.704	0.738	0.560	0.193	0.285	0.130	-0.006	-0.427	-2.438	0.139	23.9	0.750	0.1326
25		242A	2092.16	44.0	48.2	0.190	0.798	0.618	0.686	0.483	0.118	0.244	0.151	0.071	-0.141	-0.696	0.138	15.2	0.478	0.1682
26		157A	2063.06	18.6	21.0	0.183	0.736	0.741	0.936	0.655	0.286	0.374	0.267	0.175	0.016	-0.267	0.271	10.1	0.317	0.2090
27		123A	2051.71	63.5	67.5	0.178	0.823	0.825	0.881	0.681	0.321	0.412	0.283	0.157	-0.159	-1.112	0.203	18.9	0.593	0.1501
28		132A	2054.70	33.9	37.2	0.168	0.789	0.792	0.943	0.691	0.337	0.393	0.273	0.169	-0.052	-0.562	0.158	14.2	0.446	0.1745
29		171A	2067.69	5.4	6.4	0.161	0.611	0.622	0.976	0.814	0.474	0.479	0.365	0.294	0.203	0.071	0.273	5.8	0.181	0.2803
30		319A	2270.35	24.2	26.8	0.164	0.766	0.770	1.000	0.808	0.451	0.490	0.367	0.266	0.080	-0.293	0.173	12.1	0.381	0.1895
31		322A	2271.45	27.8	30.6	0.164	0.777	0.780	1.000	0.959	0.633	0.552	0.410	0.289	0.086	-0.331	0.195	13.0	0.409	0.1826

2. Swn = Sw - Swirr

Swirr

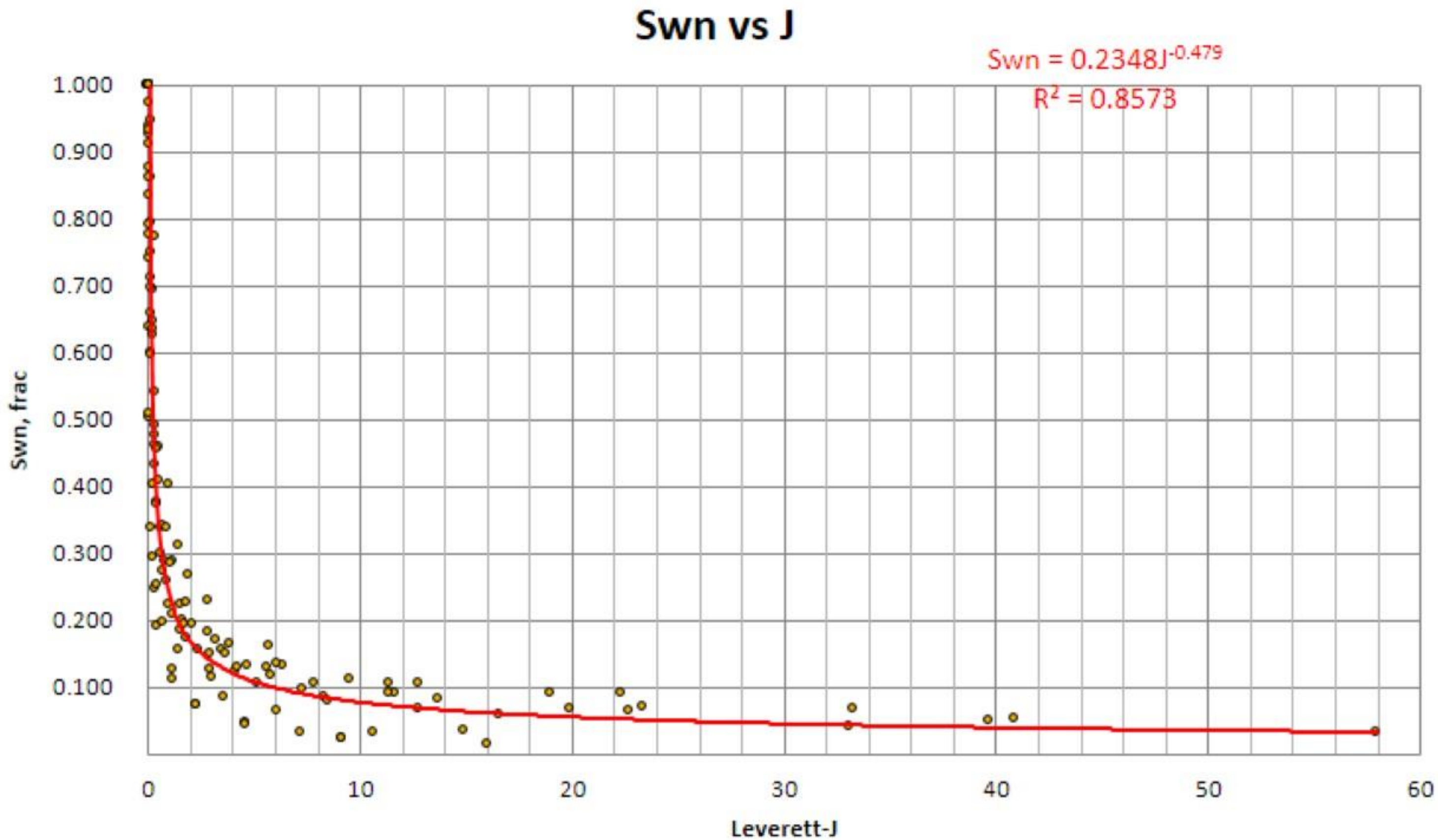


Swirr as a function of RQI
y = 0.114x^-0.527
R² = 0.7122
Adjusted Swirr = 0.09*RQI^(-0.55)
Swirr
RQI
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Swn (=Sw-Swirr)/(1-Swirr)

Pressure,				psi :	0	1	2	5	10	25	50	100	200	350			
		Net Overburden (800 psi)															
Sample ID	Depth	Klinkenberg Permeability	Permeability to air (est.)	Porosity	Swn												
	m	md	md	frac	Pore Volume, frac										Swir_final	SQRT(k/Phi)	RQI
196A	2076.47	685.	690.	0.226	1.000	0.659	0.462	0.287	0.200	0.122	0.084	0.058	0.041	0.031	0.067	55.063	1.729
91A	2040.02	332.	337.	0.220	1.000	0.861	0.692	0.300	0.207	0.148	0.117	0.092	0.070	0.051	0.081	38.823	1.219
93A	2040.68	297.	305.	0.209	1.000	0.740	0.501	0.292	0.192	0.111	0.074	0.047	0.023		0.082	37.725	1.185
89A	2039.36	211.	218.	0.212	1.000	0.936	0.710	0.377	0.224	0.156	0.131	0.111	0.092	0.066	0.090	31.564	0.991
248A	2094.07	109.	114.	0.191	1.000	0.912	0.645	0.408	0.289	0.183	0.129	0.091	0.065	0.049	0.105	23.896	0.750
105A	2044.70	90.6	95.4	0.201	1.000	1.000	0.793	0.477	0.338	0.223	0.169	0.131	0.105	0.090	0.112	21.235	0.667
123A	2051.71	63.5	67.5	0.178	1.000	0.999	0.876	0.508	0.338	0.246	0.196	0.156	0.126	0.106	0.120	18.893	0.593
75A	2034.68	49.8	54.4	0.213	1.000	0.833	0.697	0.491	0.340	0.173	0.085	0.031			0.135	15.288	0.480
242A	2092.16	44.0	48.2	0.190	1.000	0.790	0.637	0.402	0.252	0.126	0.073	0.043	0.024	0.015	0.135	15.217	0.478
132A	2054.70	33.9	37.2	0.168	1.000	1.000	0.925	0.599	0.430	0.271	0.183	0.115	0.064	0.032	0.140	14.198	0.446
322A	2271.45	27.8	30.6	0.164	1.000	1.000	0.860	0.626	0.458	0.311	0.229	0.162	0.106	0.068	0.147	13.022	0.409
319A	2270.35	24.2	26.8	0.164	1.000	1.000	0.932	0.635	0.455	0.284	0.194	0.129	0.078	0.036	0.153	12.141	0.381
157A	2063.06	18.6	21.0	0.183	1.000	1.000	0.971	0.776	0.598	0.373	0.257	0.193	0.155	0.134	0.169	10.081	0.317
171A	2067.69	5.37	6.41	0.161	1.000	1.000	1.000	0.750	0.542	0.337	0.227	0.148	0.096	0.068	0.230	5.778	0.181
23A	2017.24	4.70	5.80	0.195	1.000	1.000	1.000	0.945	0.771	0.402	0.266	0.163	0.104	0.082	0.252	4.911	0.154

Swn expressed as a function of J

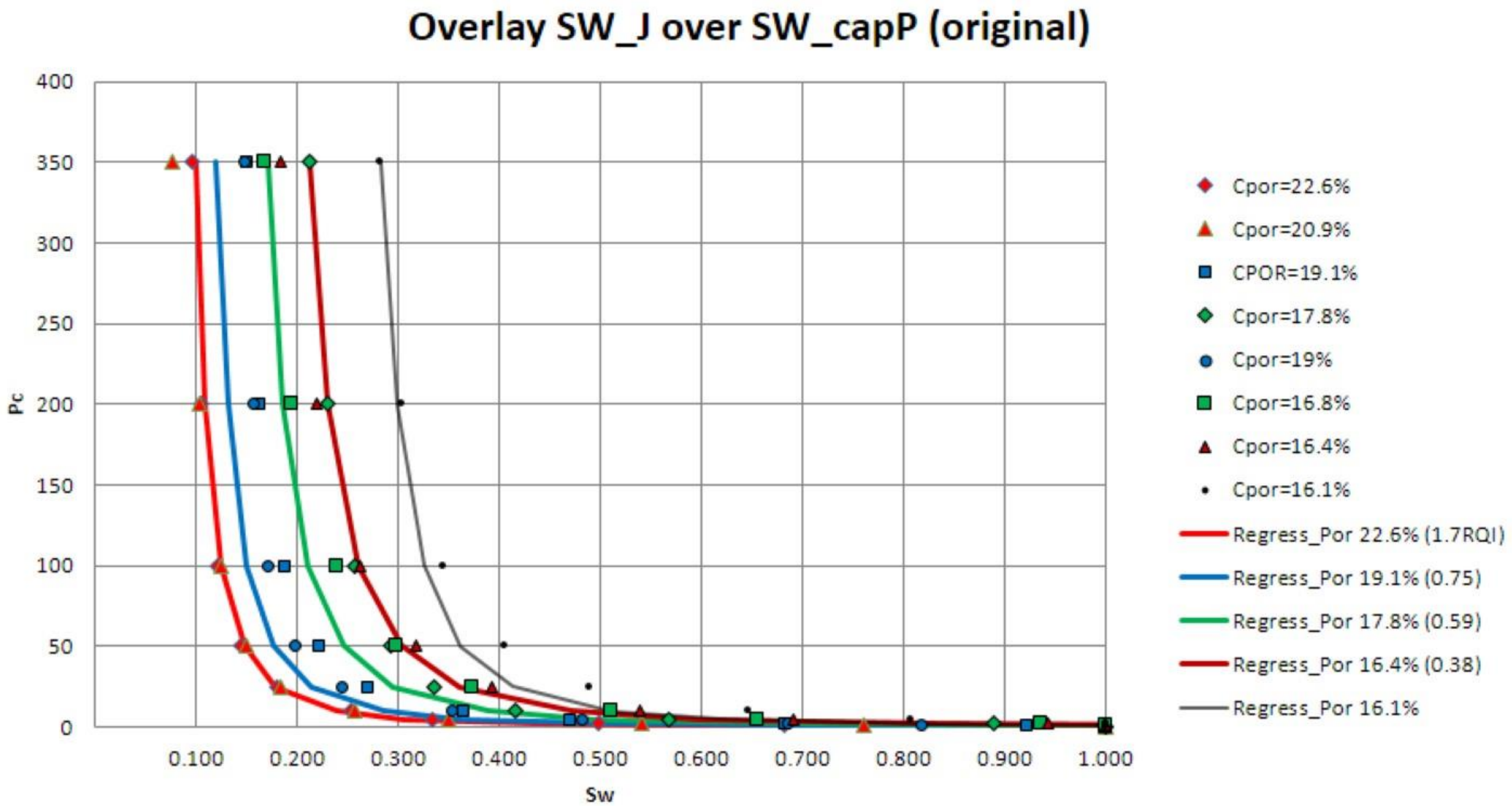


Final equations

- Swn = 0.2348*J^(-0.47) . . . .(1)
- J = 0.2166*Pc*sqrt(K/ϕ)/σcosθ . . . . (2)
- σcosθ=72 dynes/cm . . . .(3)
- Swn =0.2348*[0.003*Pc*sqrt(K/ϕ)] ^(-0.47)
- =3.596*[Pc*sqrt(K/ϕ)] ^(-0.47)
- Swirr=0.09*RQI^(-0.55)

  =0.6038*sqrt(K/ϕ) ^(-0.55) . . . . (4)
- Sw = Swn*(1-Swirr)+Swirr
- Sw = 3.596*[Pc*sqrt(K/ϕ)] ^(-0.47) *(1–0.604*sqrt(K/ϕ) ^(-0.55))+ 0.604*sqrt(K/ϕ) ^(-0.55). . . . .(5)

Final Test of the SH_Function



The SH_Function discussed above are at laboratory conditions. For reservoir condition, $T\cos\phi$ =50 dynes/cm should be used instead of 72 dynes/cm in the final equation.

Conversion to Reservoir conditions

$$\frac{Pc_L}{Pc_R} = \frac{(T \cos\theta)_L}{(T \cos\theta)_R}$$

$$\therefore \quad Pc_R = Pc_L \cdot \frac{(T \cos\theta)_R}{(T \cos\theta)_L}$$

For air-brine system, $P_{cR} = P_{CL}*50/72$

Final equations at reservoir conditions

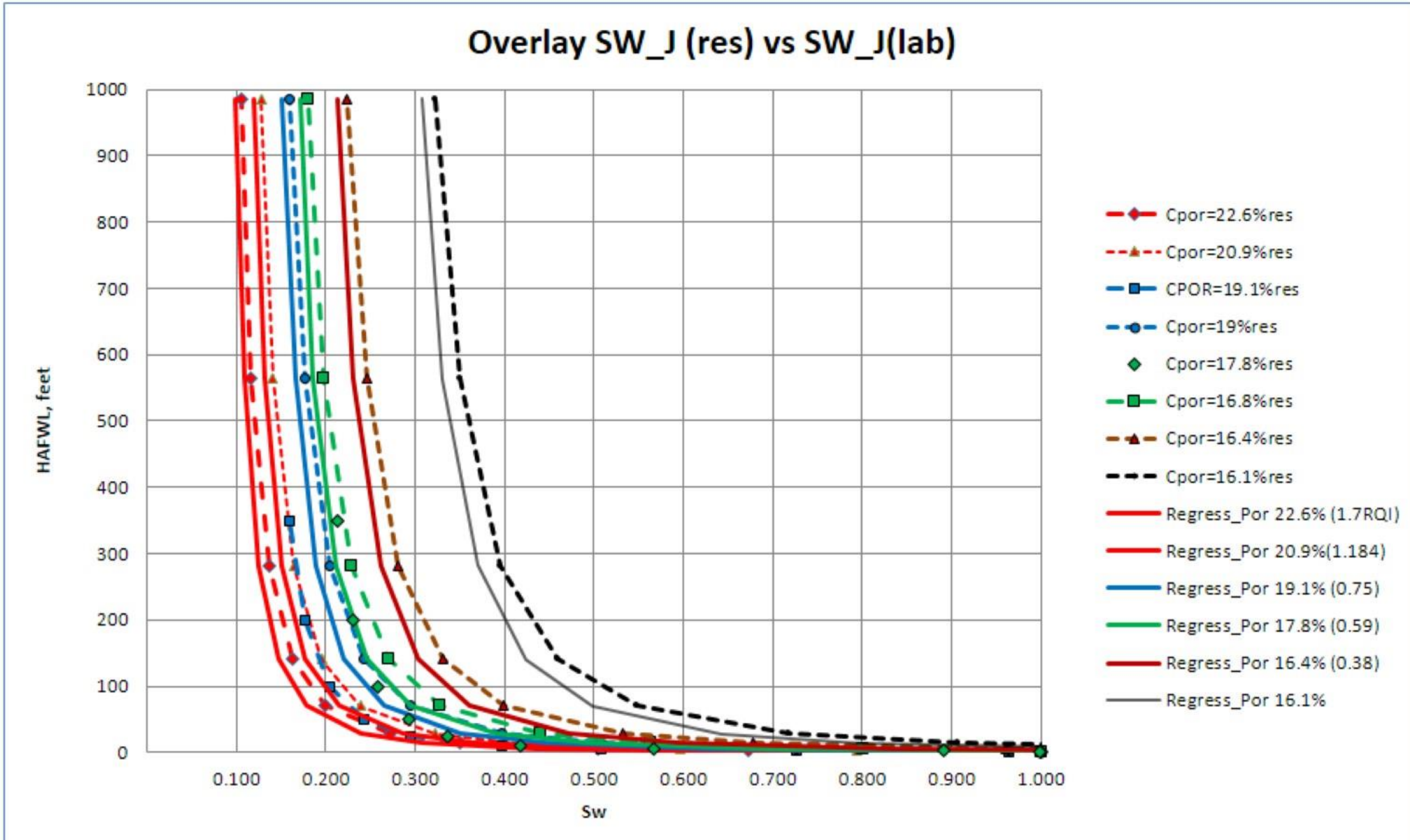
- Sw = 3.596*[Pc*sqrt(K/ϕ)] ^(-0.47) *(1–0.604*sqrt(K/ϕ) ^(-0.55))+ 0.604*sqrt(K/ϕ) ^(-0.55) . . . . .(5)

- Sw(res) = 3.596*[Pc*(50/72)*sqrt(K/ϕ)] ^(-0.47) *(1–0.604*sqrt(K/ϕ) ^(-0.55))+ 0.604*sqrt(K/ϕ) ^(-0.55). . . . .(6)

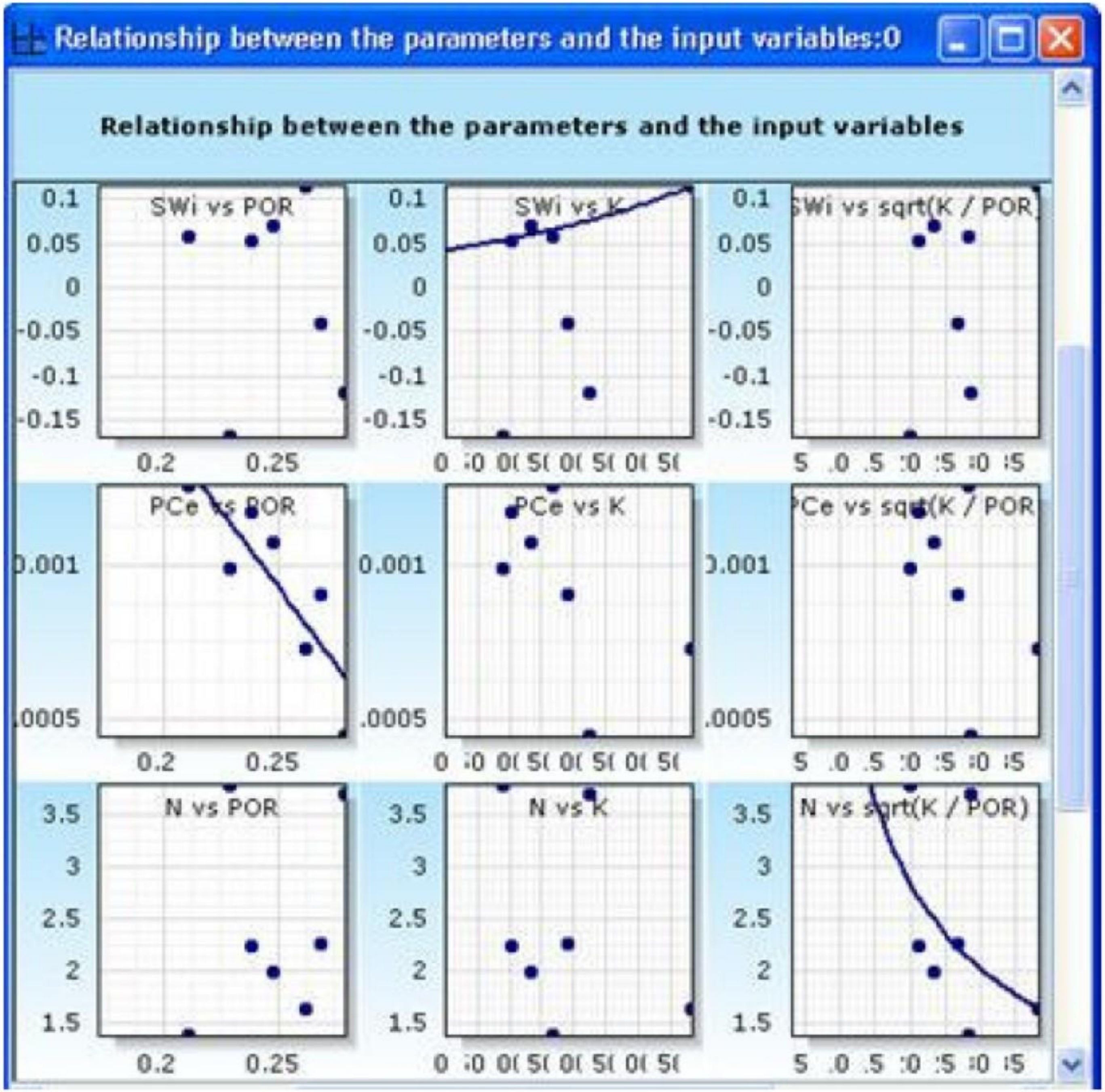
- Sw_res = 3.596*[((ρ_{water} – ρ_{Gas})*H *(50/72)*sqrt(K/ϕ)] ^(-0.47) *(1–0.604*sqrt(K/ϕ) ^(-0.55))+ 0.604*sqrt(K/ϕ) ^(-0.55). . . . .(7)

where H is the height above free water level in feet and ρ_{water} and ρ_{water} are in psi/ft.

Comparison of SW_J(res) with SW_J(lab)




Relationship between the parameters and the input variables:0
Relationship between the parameters and the input variables
SWi vs POR
SWi vs K
SWi vs sqrt(K / POR)
PCe vs POR
PCe vs K
PCe vs sqrt(K / POR)
N vs POR
N vs K
N vs sqrt(K / POR)
0.1
0.05
0
-0.05
-0.1
-0.15
0.001
0.0005
3.5
3
2.5
2
1.5
0.2
0.25

Number of regressions to investigate

The different regressions are:

1. Linear $P = C_1 + C_2 * INPUT$
2. Logarithmic $P = C_1 + C_2 * \log 10(INPUT)$
3. Power $P = C_1 * pow(INPUT, C_2)$
4. Exponential $P = pow10(C_1 + C_2 * INPUT)$