High Pressure Mercury Injection Capillary Pressure:

unveiling its value by scrutinising and analysing disparate data sets into a single, meaningful analysis

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Lloyd's Register

Agenda

- Background
- Data Evaluation
- Data Interpretation
- Conclusions

Capillary Pressure Curves

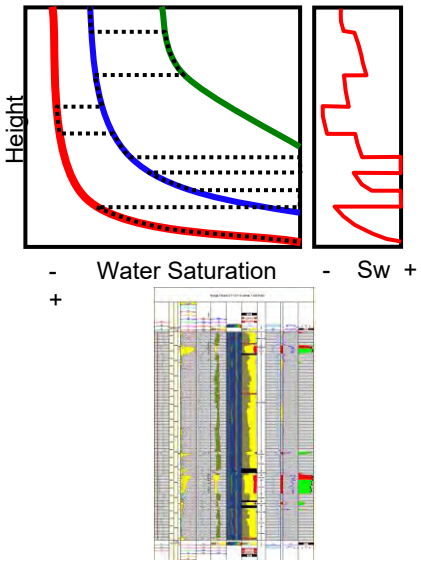
Reservoir to Lab:

$$Sw = f\,(H)$$

$$H = f\,(Pc)$$

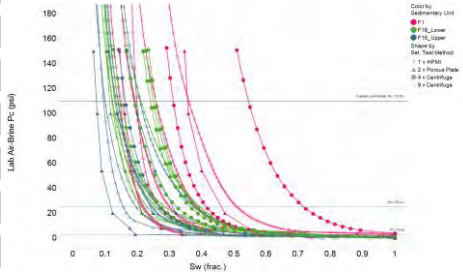
$$Sw = f\,(Pc)$$

Lab to Reservoir



$$H = \frac{Pc}{\Delta\rho \,.\, g}$$

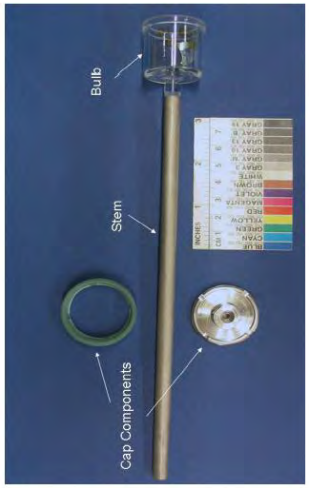
Pc (Res. Conditions) vs. Sw

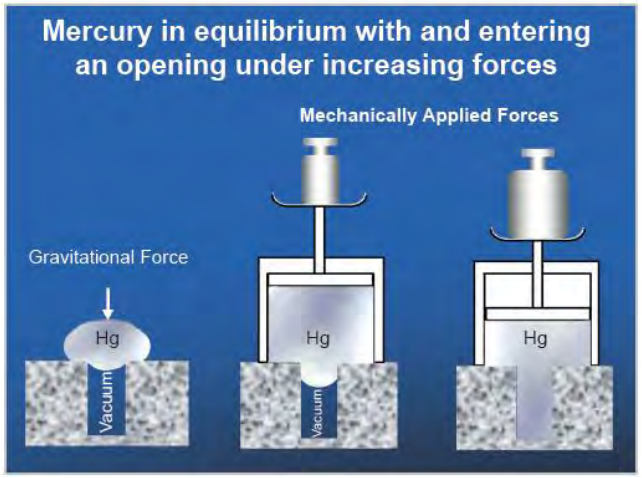


Pc (Lab Conditions) vs. Sw

High Pressure Mercury Injection (HPMI)

- MICP used extensively for Pc tests design, Sw-Height, rock quality and typing





- Max. sample size is 1" dia. x 1" length plug
- Relatively cheap and fast (several samples per day)
- Uses clean-dry samples
- Mercury does not wet most substances
- Very high pressures up to 60,000 psi are achieved (0.001 microns pores)
- It does not spontaneously penetrate pores by capillary action
- It must be forced into the pores by the application of external pressure
- HPMI is the progressive intrusion of mercury into a porous structure under extremely controlled pressures
- Hg volumes are not measured directly, but calculated based on a change of capacitance as Hg leaves the stem of the penetrometer (a capillary) to intrude the sample, for each pressure
- From the pressure versus intrusion data, the instrument generates volume and size distributions using the Washburn equation

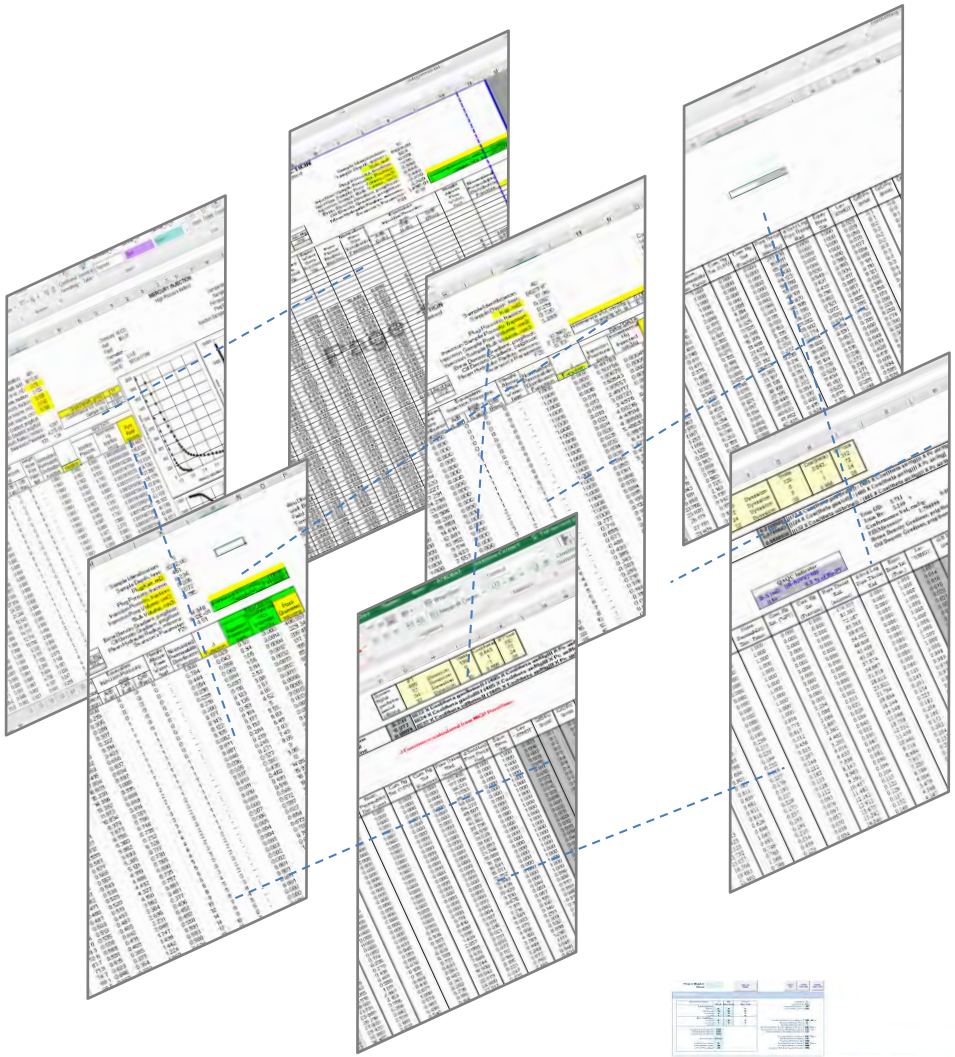
www.micromeritics.com/Repository/Files/Mercury_Porosemitry_Theory_poster_.pdf

Sigal 2009. "A methodology for blank and conformance corrections for high pressure mercury porosimetry"

Case Study

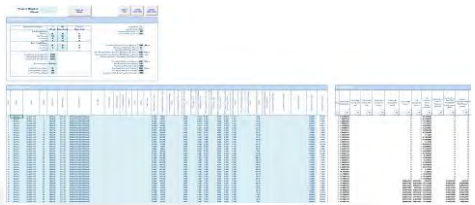
- Total of ~ 2000 HPMI Pc curves from ~ 50 wells (same field)
- Source files of various vintage (age) and measured in different laboratories
- Objectives:
  - Effectively load all available data into a single data base
  - Asses quality of data
  - Identify limitations / highlight suspect data
  - Provide preliminary insights for potential rock quality grouping (rock typing)

Data Preparation



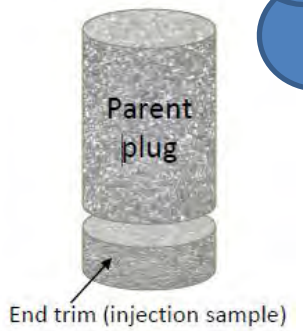
- Recognition of available data – what's reported?
- Patterns recognition – grouping identical input formats

- 7 different types of Source Data Files were identified, all requiring different data loading algorithms
- Software to automate as much as possible data loading and QC was developed



Data Preparation

This is the main data required, anything else can be calculated from here



- Field, well
- Formation (if available)
- Sample Number
- Sample Depth
- Permeability (measured or Parent Plug)
- Porosity (measured)
- MICP sample He Grain Volume
- MICP sample He Pore Volume
- MICP sample Hg Immersed Bulk Volume
- MICP sample He Porosity (He GV + Hg imm. BV) (reported or calculated)
- Sample weight – if injection data provided in cc/g
- Mercury Injection Pressure
- Hg injection volume
  - Incremental Hg Injected (cc/g) or Cumulative Hg Injected (cc/g)

  or
  - Incremental Hg Injected (cc) or Cumulative Hg Injected (cc)

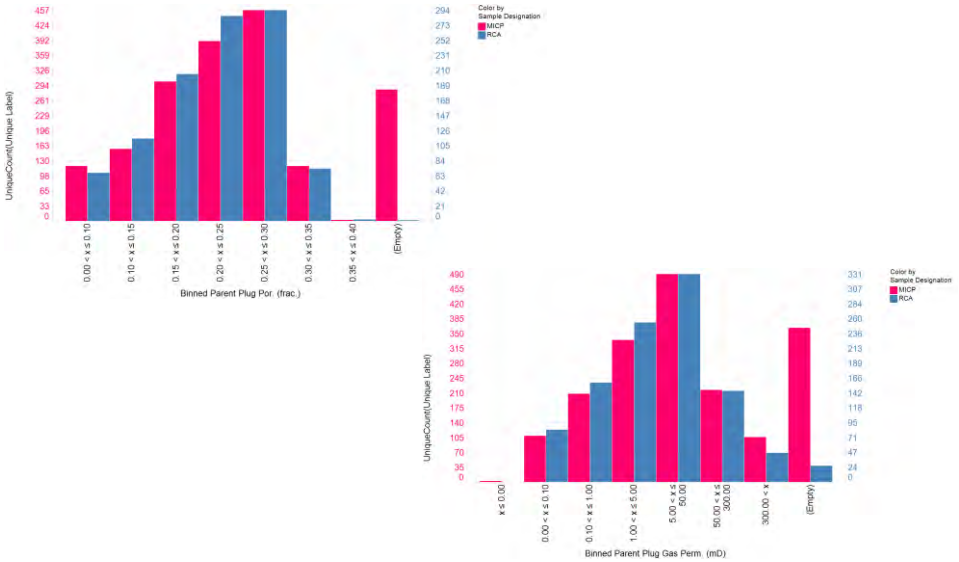
Quality System

1	Use data with confidence
2	Sample Suspect - use data with care
3	Reject Sample - unacceptable data or uncertainty

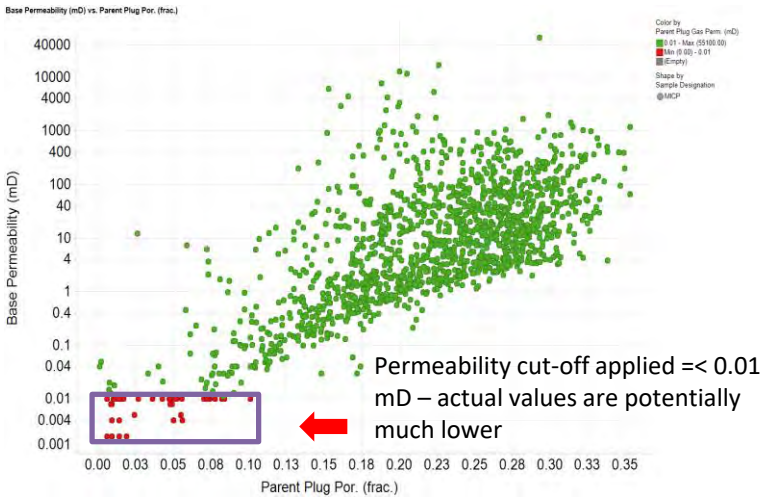
- Data Availability:
  - Porosity and permeability, MICP sample He Pore Volume, raw injection data (pressure and Hg volume), etc.
- Values:
  - MICP sample Pore Volume, MICP sample He PV vs. Hg PV, MICP sample Porosity vs. parent plug Porosity, MICP sample Grain Density vs. parent plug Grain Density, penetrometer size (if available)
- Curve Shape / Trends:
  - Pc vs. Saturation
  - Swi vs. Porosity, Permeability and RQI
  - J Leverett
  - Etc.

MICP Sample Poroperm

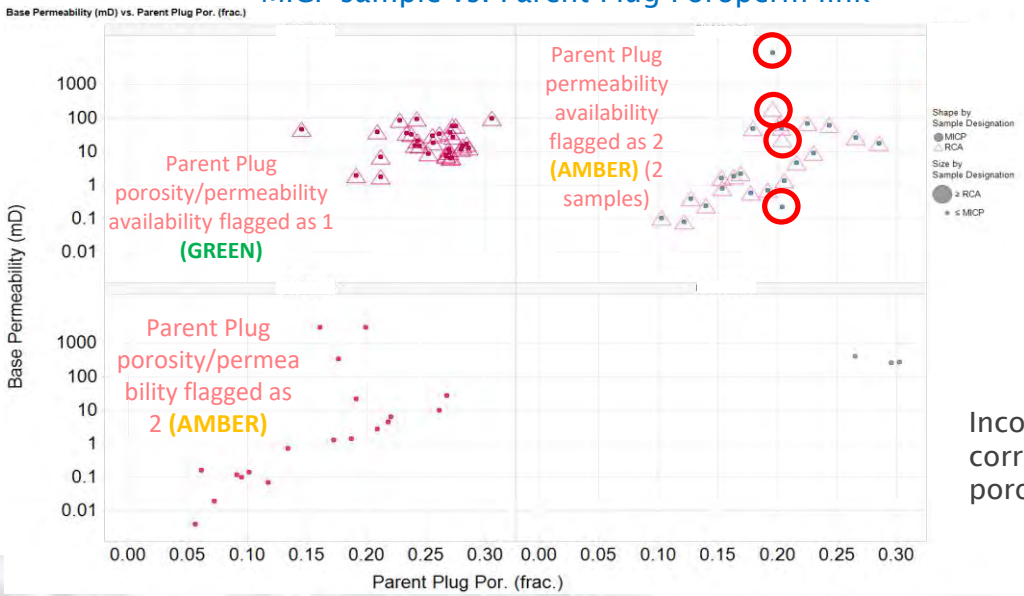
MICP samples coverage



Cut-off Values

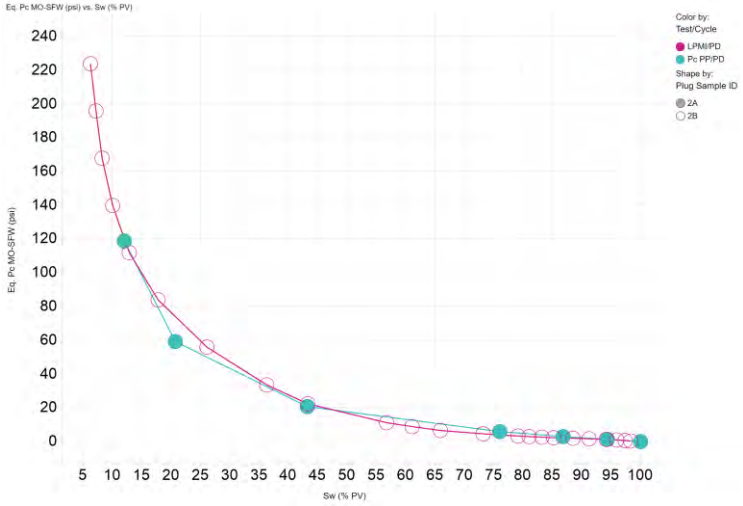


MICP sample vs. Parent Plug Poroperm link

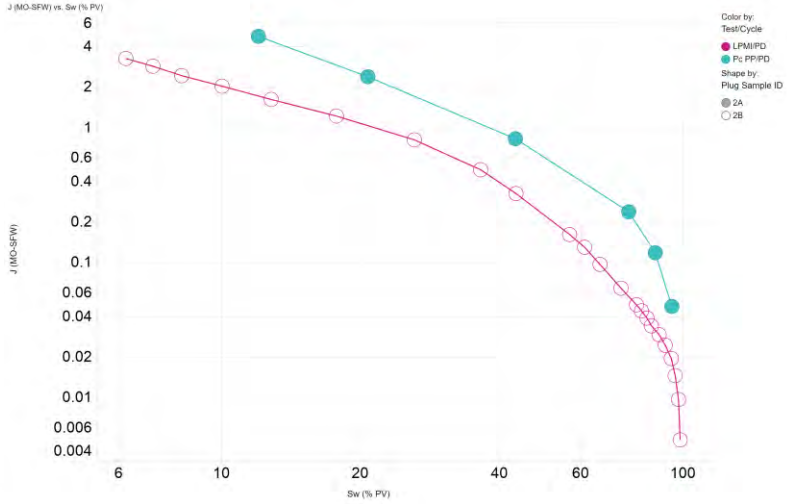


Inconsistencies between MICP and corresponding “sister” RCA sample poroperm data were identified

Importance of Reliable MICP Sample Poroperm Data



$$J_{Sw} = \frac{0.2166 Pc}{\sigma \cos\theta} \sqrt{\frac{ka}{\phi}}$$

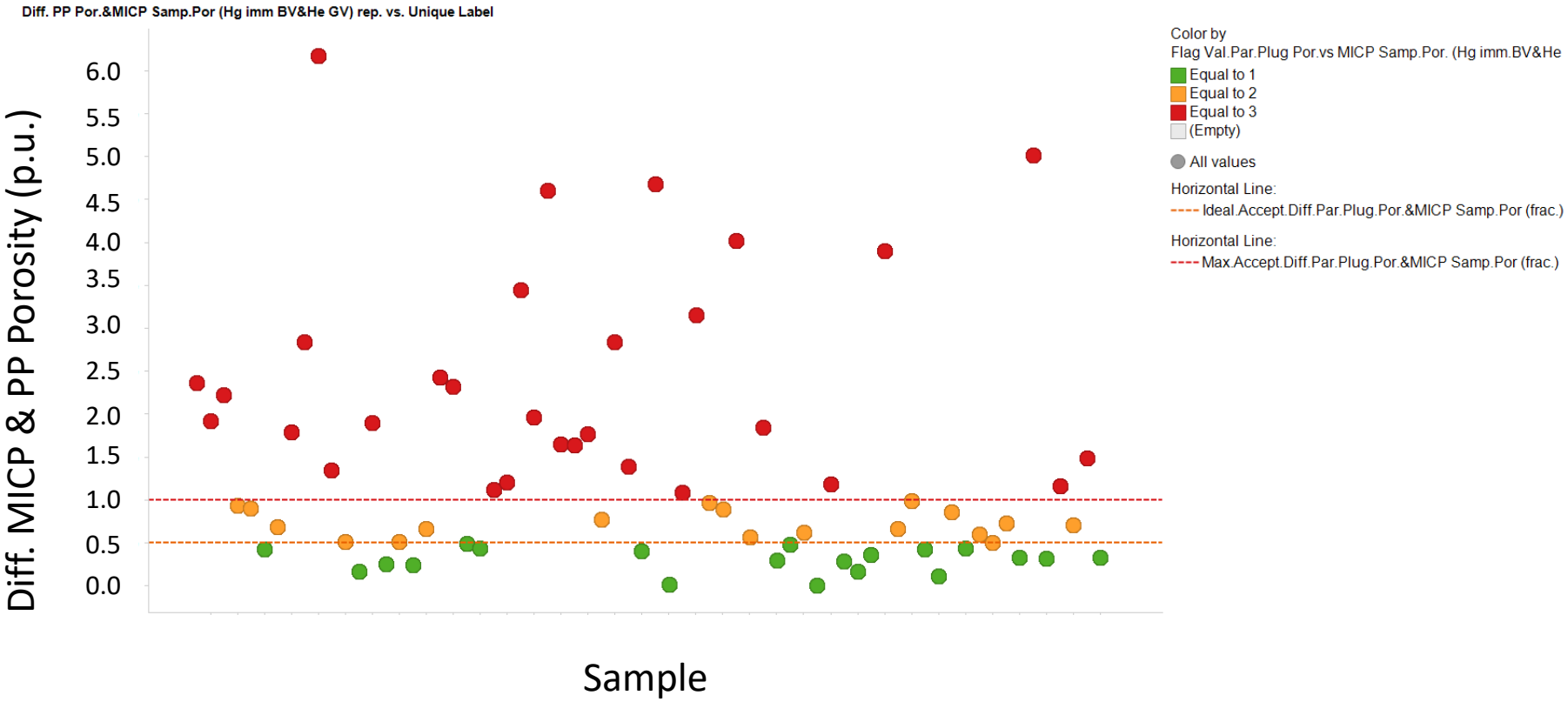


- K values for sister samples 2A and 2B very different:
  - typo
  - error in measurement
  - truly not the same rock quality
- Uncertainty in base data translates into any further use of MICP data, specially for modelling purposes

Sample	Depth (ft)	Overburden Pressure (psig)	Permeability to Air (md)	Porosity (% BV)	Grain Density (gm/cc)
1A	9733.5	500	1.55	13.4	2.70
		2000	1.43	13.3	
		4000	1.38	13.2	
		6000	1.32	12.8	
1B		200	3.60	17.5	2.70
1C		200	1.21	12.2	2.70
2A	9736.5	500	12.0	20.2	2.70
		2000	10.9	19.9	
		4000	10.2	19.9	
		6000	9.53	19.6	
2B		200	1.42	18.1	2.69
2C		200	2.61	19.9	2.69
3A	9750.5	500	8.52	20.2	2.69
		2000	8.18	20.0	
		4000	7.90	19.9	
		6000	7.58	19.7	
3B		200	6.20	19.4	2.68
3C		200	5.60	20.1	2.69
4A	9757.5	500	4.03	21.9	2.68
		2000	3.70	21.3	
		4000	3.59	21.0	
		6000	3.28	20.7	
4B		200	3.87	21.2	2.69
4C		200	4.82	23.1	2.71

MICP Sample Poroperm

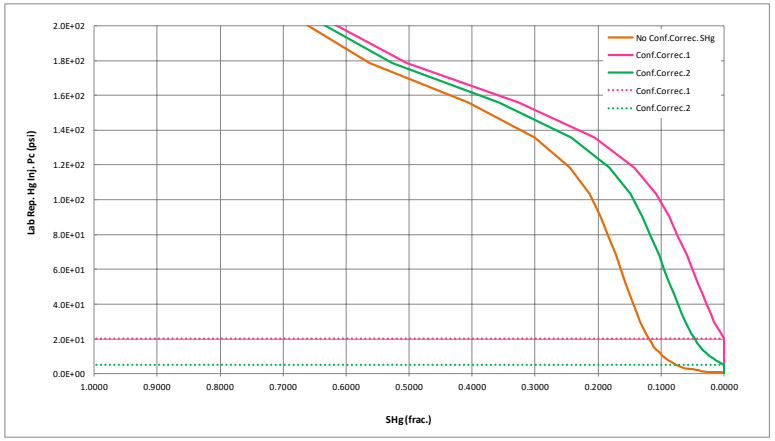
MICP and corresponding “sister” RCA sample porosity comparison



Conformance Correction

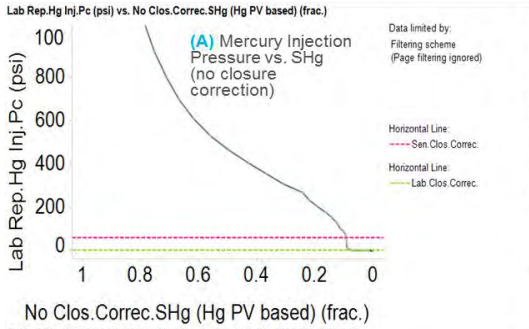
Before Mercury Injection

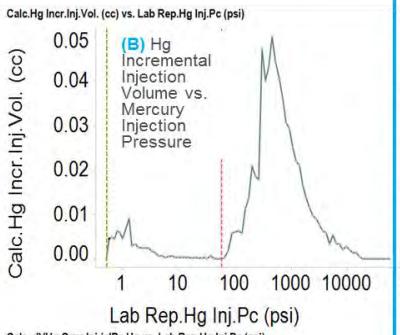
Mercury conforming to sample surface before invading "porous media"

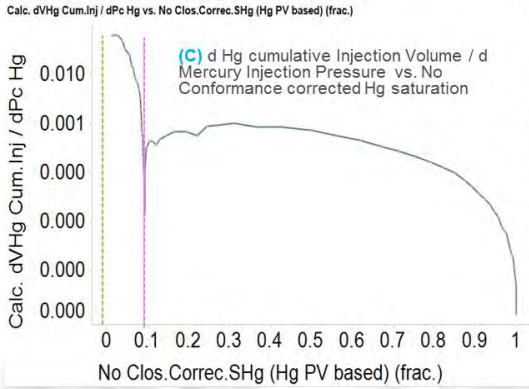


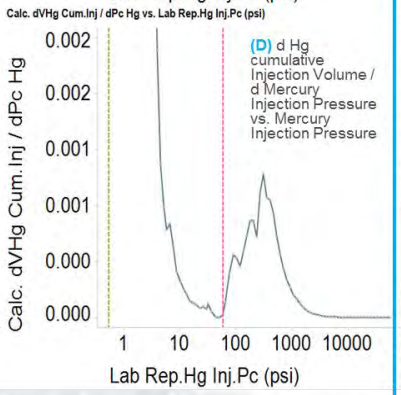
Diagnose Tools

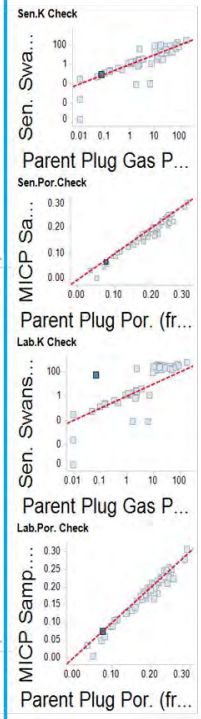
Conformance correction "checked" for each sample against "expected" porosity and permeability (compared to parent plug data (when available)). MICP Sample K from Swanson and porosity from Hg inf. (closure corrected+ He GV)











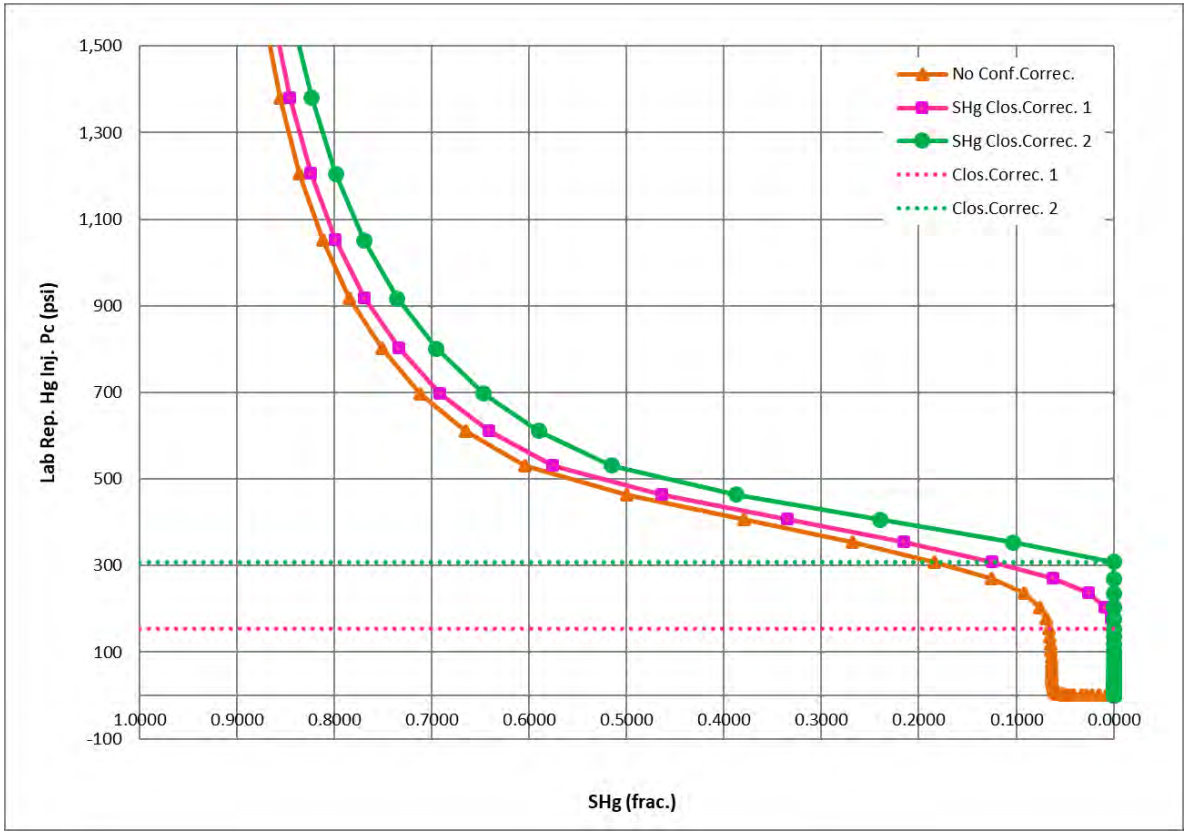
(E)

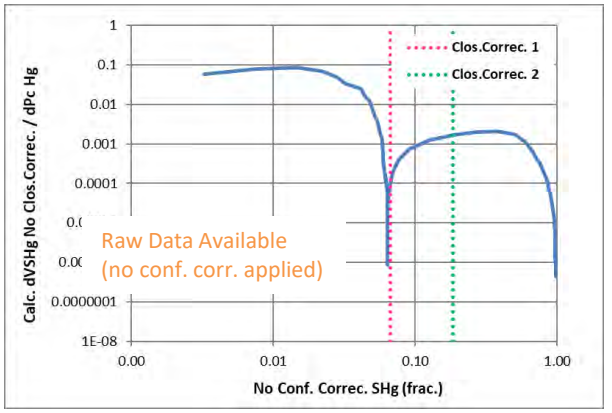
LR's

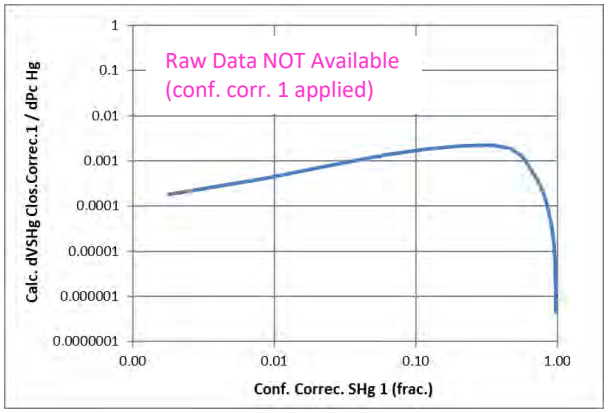
Lab's

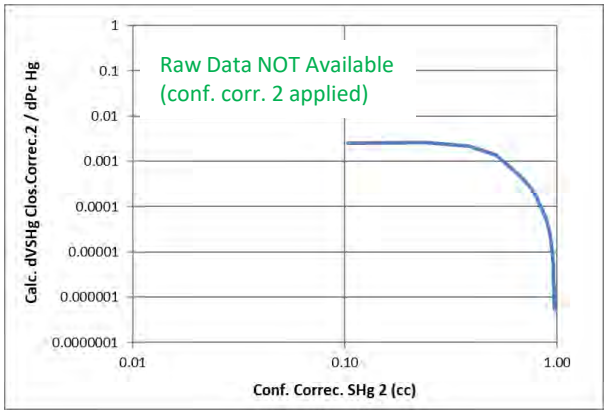
Conformance Correction

What if injection data (raw data) is not available (only SHg vs. Pc curves reported)?



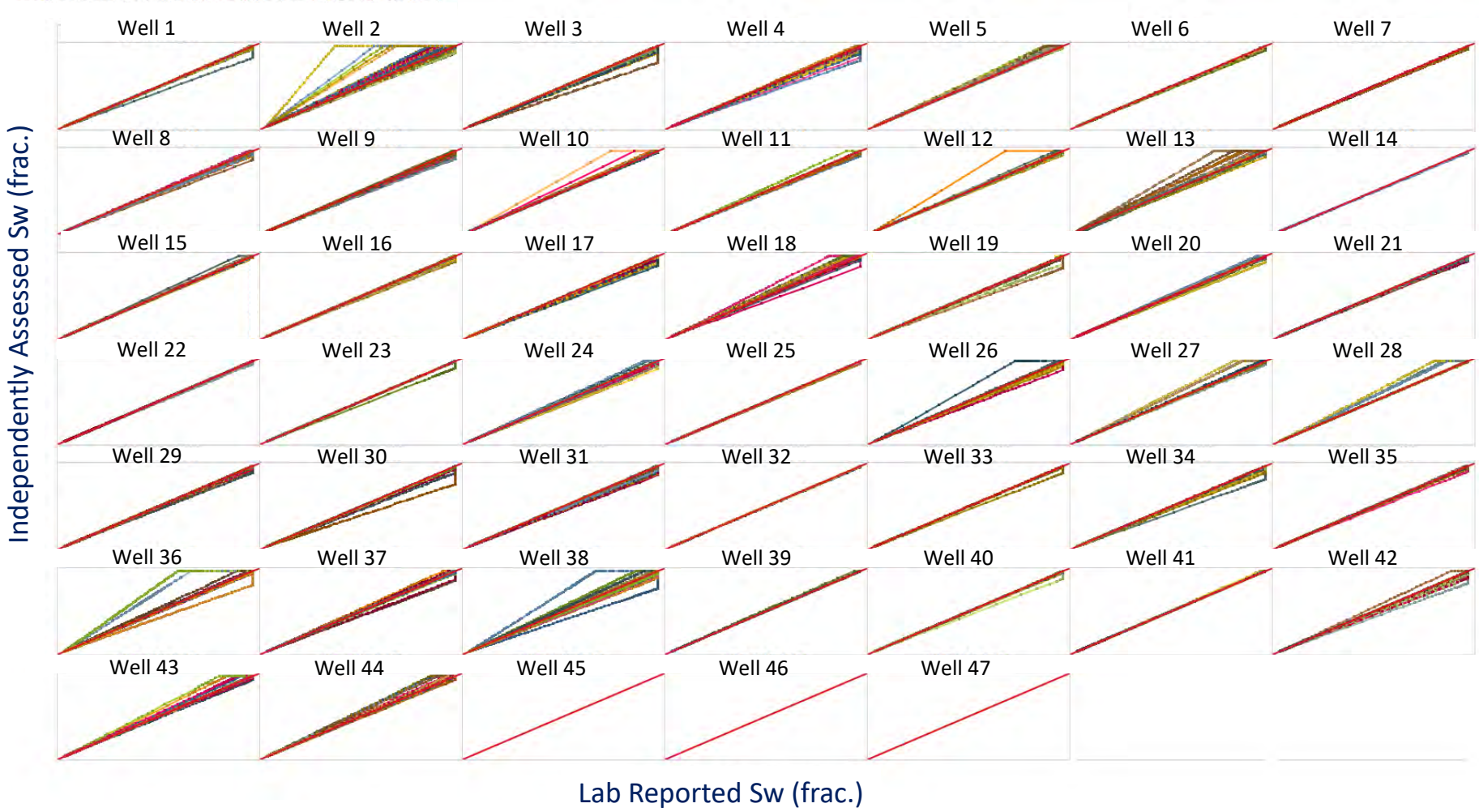






Conformance Correction

Lab vs. Independently Assessed MICP Conformance Corrections



Sample Size/Shape

LPMI

1.5” x 2.5” plug
Vb = 72 cc
ϕ= 0.20
PV = 14.4 cc

LPMI & HPMI max

1.0” x 1.0” plug
Vb = 13 cc
ϕ= 0.20
PV = 2.57 cc

HPMI typical

HPMI
Vb = 5 cc
ϕ= 0.20
PV = 1 cc

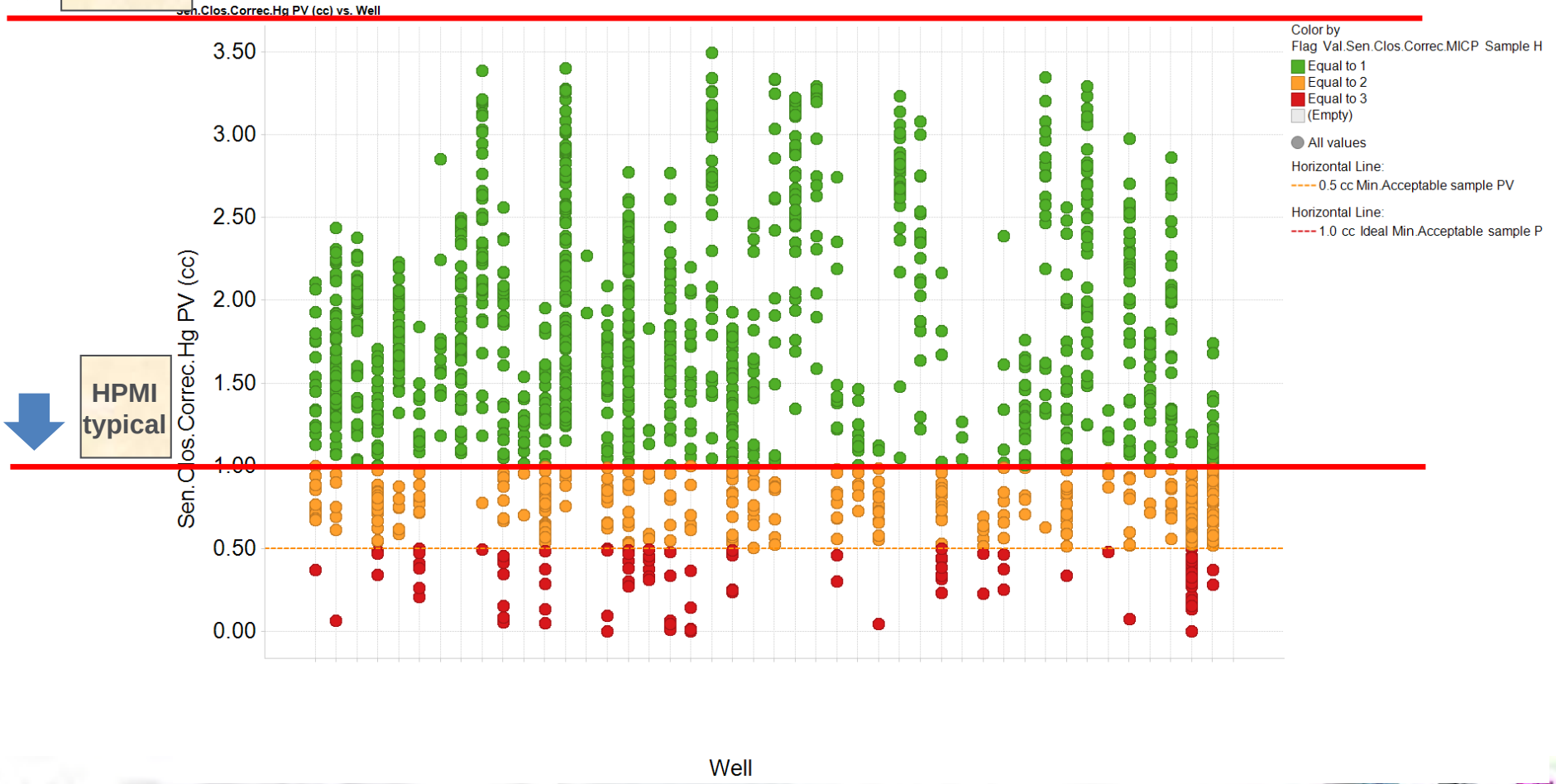
- HPMI as large as possible (1” diameter x 1” length plugs) but still compatible with penetrometer capacity
- Idea is to minimise surface area to volume ratio of samples to minimise conformance corrections (the larger the sample, the better). This also requires samples to be preferable cylinders rather than trims (when possible)
- It is not possible to measure permeability directly in plug trims, therefore an estimate value needs to be assigned, which is subject to uncertainty
- Ideal “minimum” sample pore volume for this test is ~ 1 cc (accuracy of intrusion function of stem volume)

Target Sample Pore Volume	Sample Size / Bulk Volume	Minimum Required Sample Porosity
0.50 cc (minimum required)	1” dia. x 1” length / 13 cc	3.85 %
1.00 cc (ideal minimum)	1” dia. x 1” length / 13 cc	7.70 %

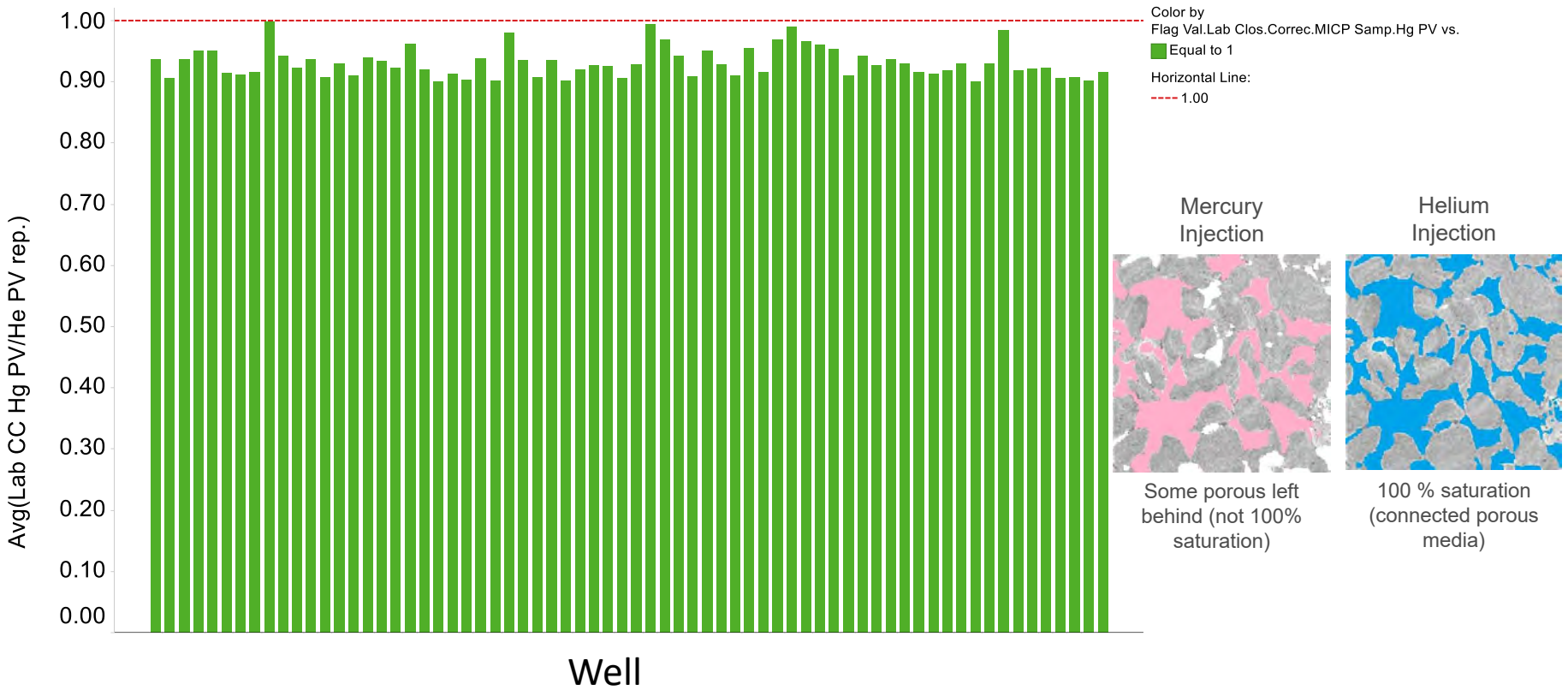
Sample Size

LPMI & HPMI max

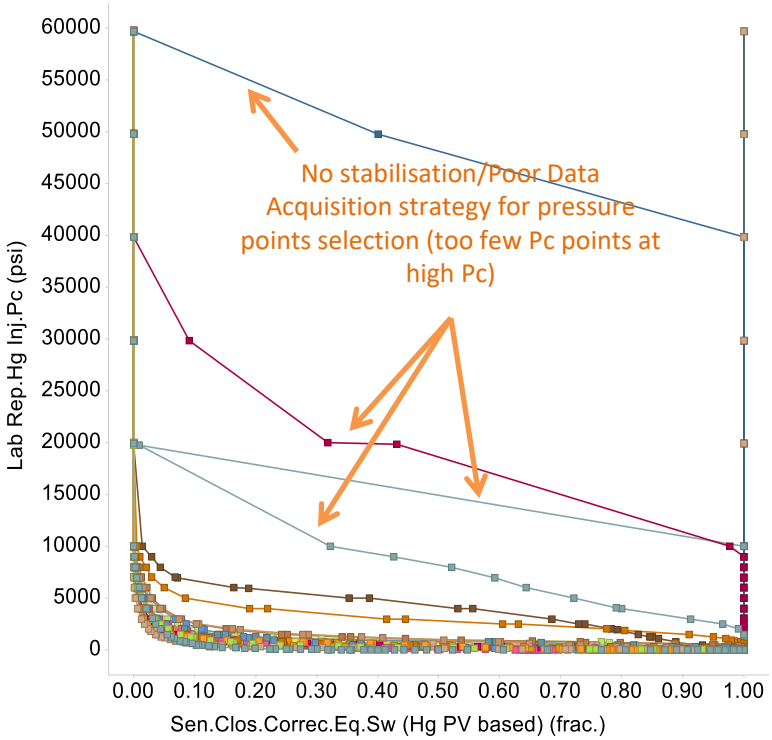
HPMI typical

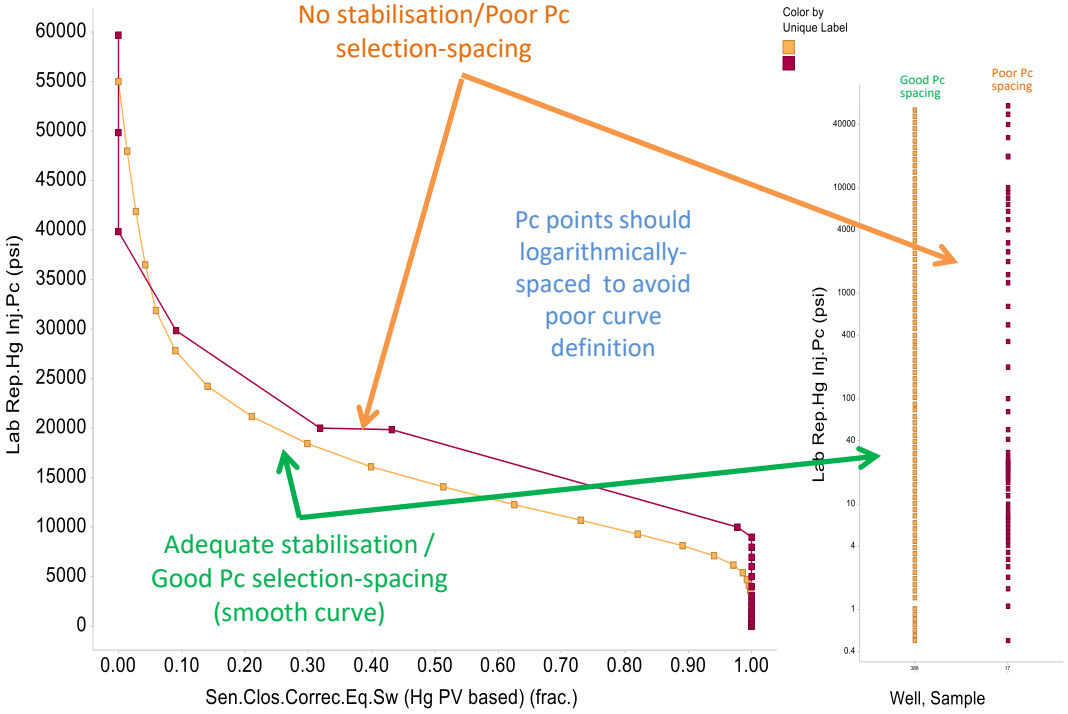


He PV vs. Hg PV


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Avg(Lab CC Hg PV/He PV rep.)
Well
Color by
Flag Val.Lab Clos.Correc.MICP Samp.Hg PV vs.
Equal to 1
Horizontal Line:
1.00
Mercury Injection
Helium Injection
Some porous left behind (not 100% saturation)
100 % saturation (connected porous media)

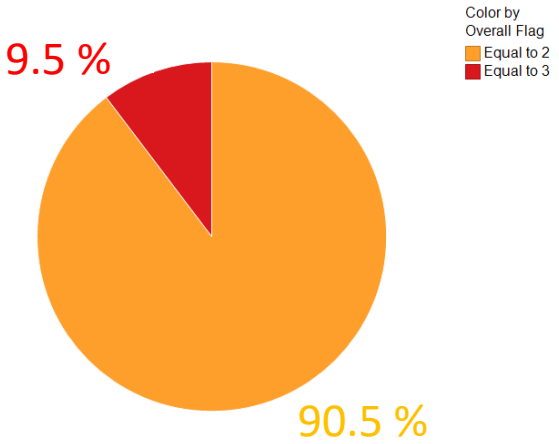
Curve Shape, Pressure Steps and Equilibration





Summary of Quality Flags

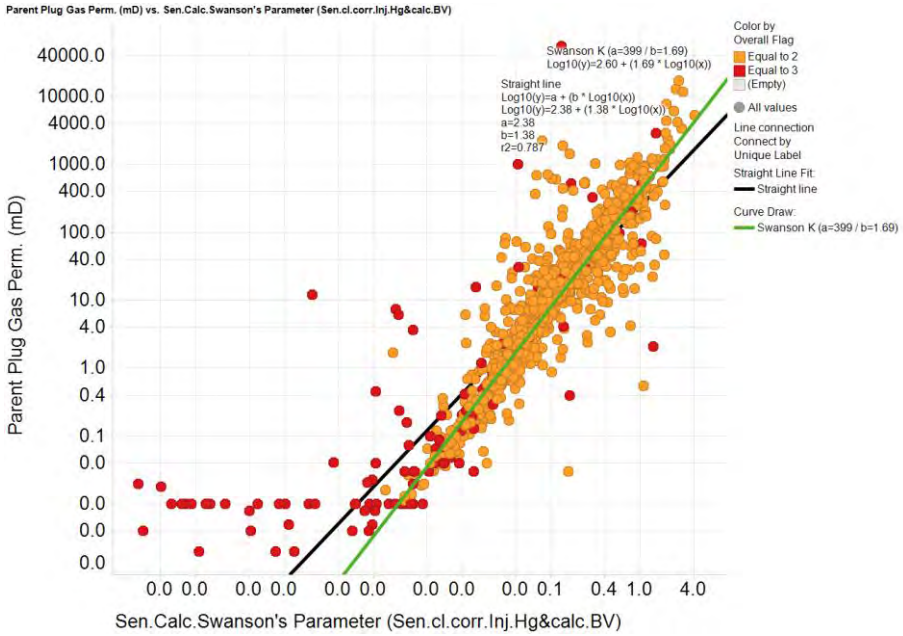
Overall Flag	Overall Data Availability Flag	Overall Values Flag	Overall Curve Shape Flag	% Samples
2	2	1	1	49
				0.5
		2		25
				16
			Sub-Total (% samples)	90.5
3	2	1	3	0.5
		2		0.5
		3	1	6
			3	0.5
				2
			Sub-Total (% samples)	9.5

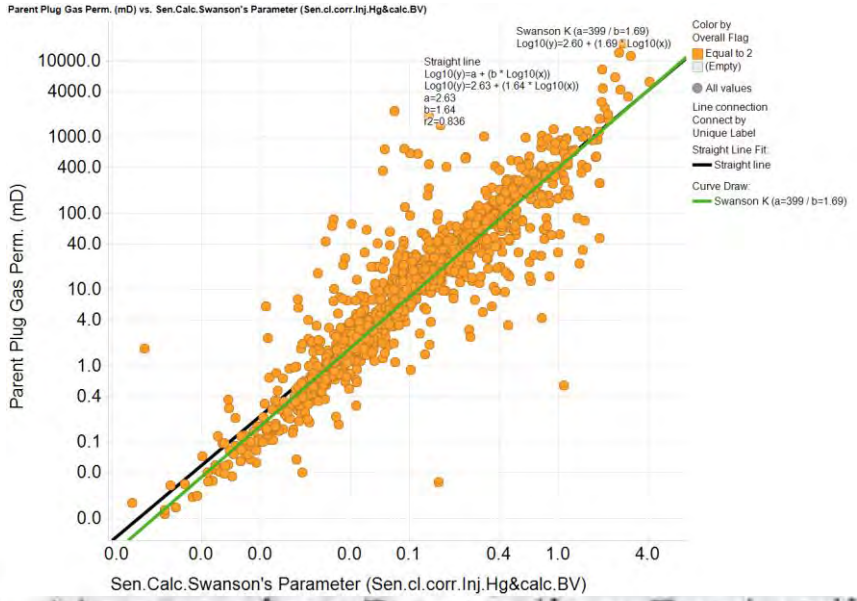


Summary of Overall QC:

- 9.5 % of samples have been rejected (highlighted as 3 (RED))
- The remaining 90.5 % have been highlighted as 2 (AMBER). These can be carried forward but are classified as uncertain
- None of the samples have been highlighted as 1 (GREEN)

Permeability Prediction





- Non QC MICP data produces the following Swanson type permeability correlation based on the independent calculation of Swanson Parameter (Sb/Pc)m max, per sample:

$$Ka = 240.\left(\frac{Sb}{Pc}\right)_A^{1.38}$$

Correlation coefficient = 0.787

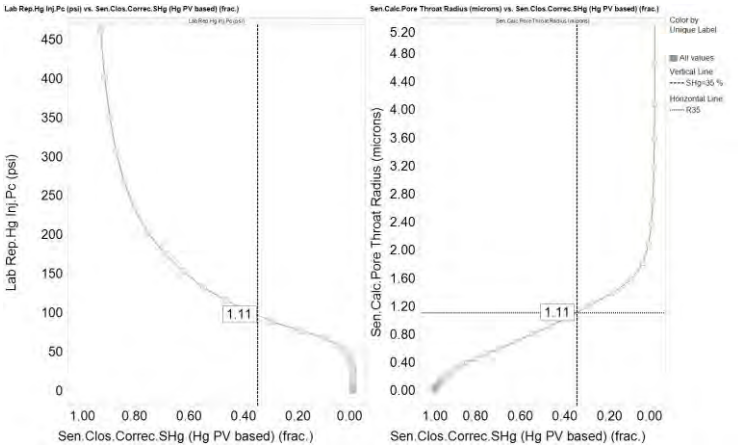
- QC MICP data produces the following Swanson type permeability correlation based on the independent calculation of Swanson Parameter (Sb/Pc)m max, per sample:

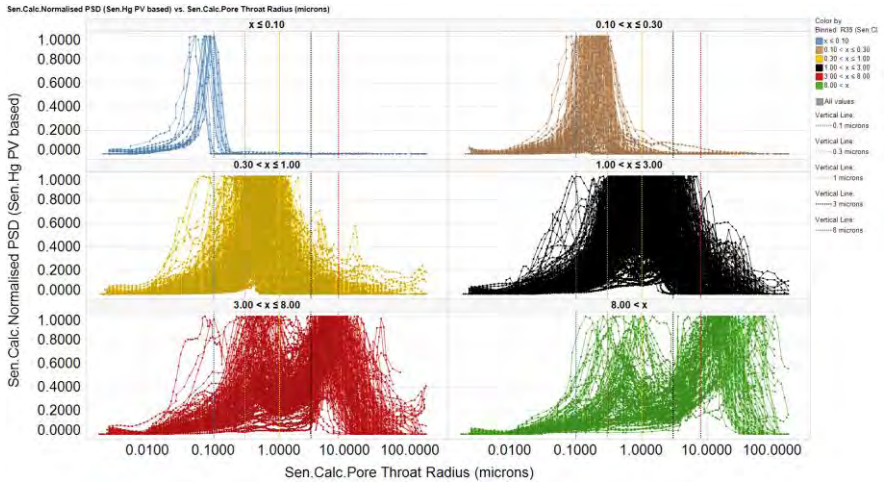
$$Ka = 427.\left(\frac{Sb}{Pc}\right)_A^{1.64}$$

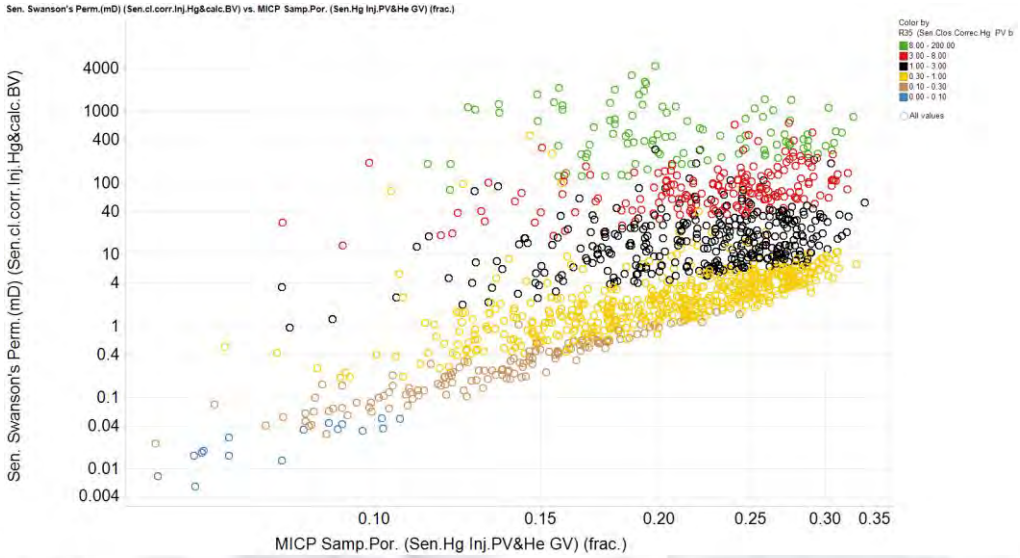
Correlation coefficient = 0.836

Reservoir Rock Quality

- **R35:**
  - Pore apertures corresponding to a mercury (non-wetting phase) saturation of 35 % (R35) were read for each one of the MICP curves (linear interpolation applied to find the exact 35% value)







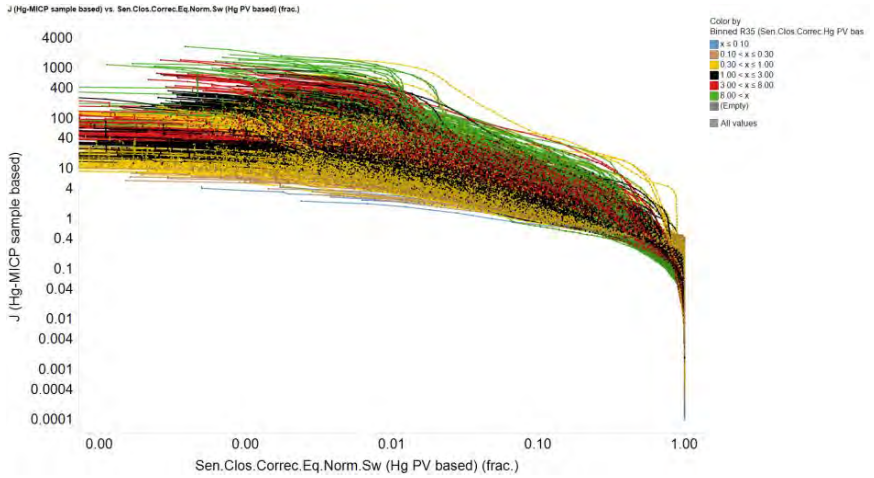
Multivariable regression of the MICP data (R35, K and Phi) was used to derive a "Winland R35 type" equation, using exclusively measured MICP data from field under study:

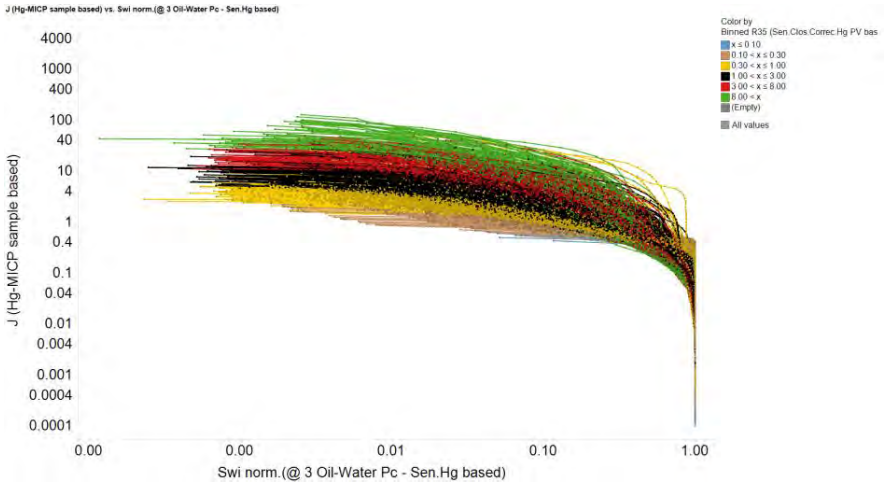
$$\text{Log R35} = 0.5699 + 0.5783\ (\text{LogK}_{\text{air}}) - 0.7796\ (\text{Log}\,\phi)$$

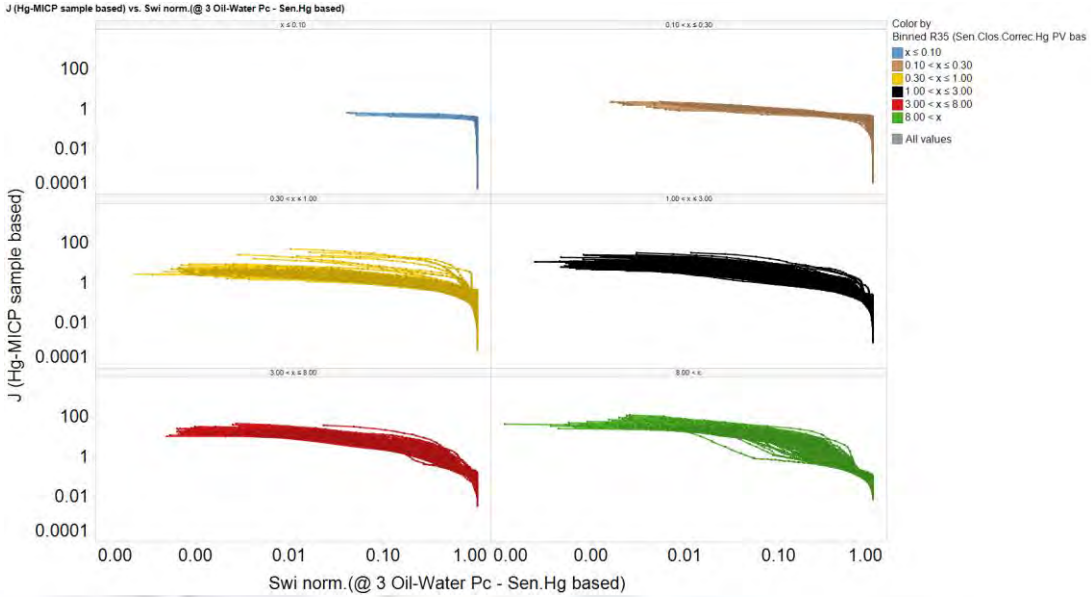
Multiple Regressions Statistics **Field based** "Winland R35" type curve:

Multiple R	0.969761525
R Square	0.940437415
Adjusted R Square	0.94034845
Standard Error	0.130320538
Observations	1342

Leverett J-Function

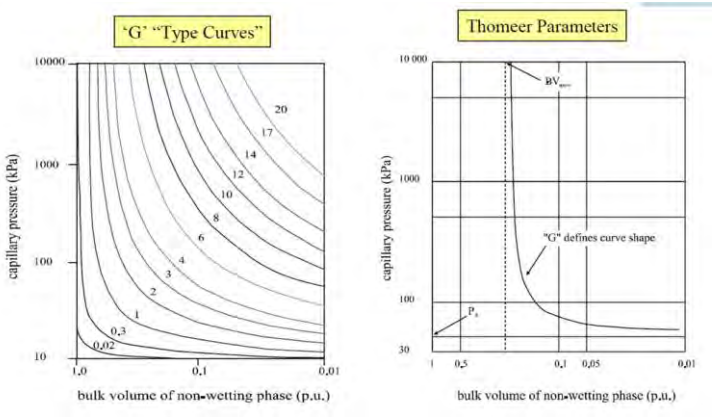




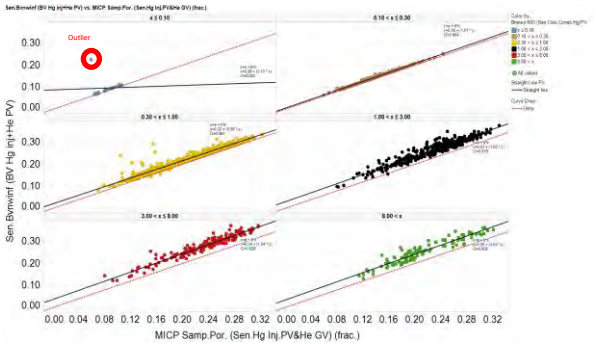


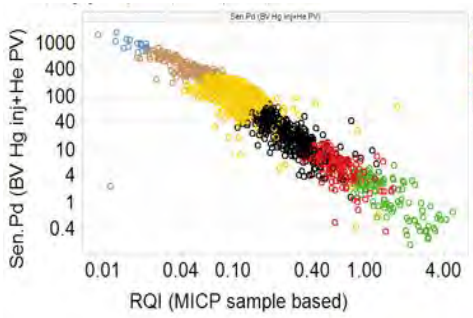
J function relationships effectively discriminated by R35 bins at normalized Swir

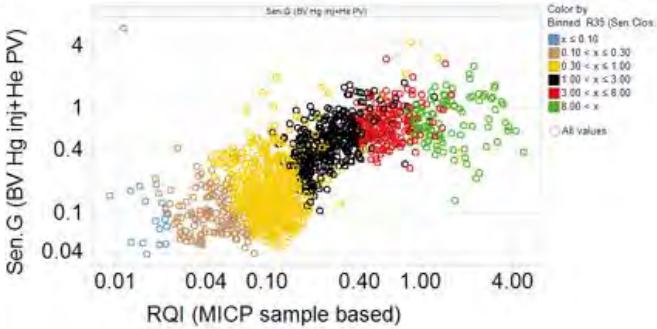
Thomeer Curve Fitting / Clustering

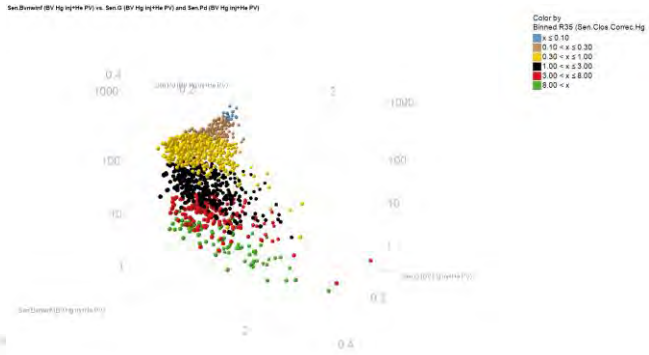


$$(1 - S_{wet}) = \frac{BV_{nw\infty}}{\phi} * e^{\left(\frac{-G}{\log_{10}\left(\frac{P_c}{P_d}\right)} \right)}$$









Conclusions

- Automatic HPMI data loading and evaluation in house algorithms have proved to be an effective and efficient way of combining disparate data sets, that otherwise would have been difficult to evaluate efficiently (let alone typos from manual processing and evaluation!!)
- A thorough and systematic review and quality control analysis of the MICP database have rejected 9.5% of the samples
- Unfortunately, none of the remaining 90.5% of samples satisfy the rigorous green QC flag criteria due mainly to the lack of experimental data and supporting information to gain confidence on the results
- Although the “acceptable” database has some limitations, the MICP data do exhibit well-developed and consistent trends that can be can be used for permeability prediction and rock typing
- Saturation-height model implementation may be possible using R35 bins and RQI to help discriminate petrophysical rock types
- There appears to be sufficient differentiation between the MICP curves’ J and Thomeer parameters and rock properties discriminated by R35
- The key to optimisation of Sw-H modelling is the identification of the rock types (defined by R35 bins, for example) from logs in uncored intervals and wells

Thank you, Any Questions?