SOCIETY OF
CORE ANALYSTS

PREMIER
COREX

Relative Permeability Measurement, Correlation, Simulation

Jules Reed – September 2020

Overview

- Measurement
  - Factors affecting relative permeability
  - Unsteady state
  - Steady state
  - Centrifuge
- Correlation
  - Parameterisation
  - Relative permeability models
- Simulation
  - Coreflood simulation for relative permeability derivation
- Conclusions

Relative Permeability - Introduction

Relative Permeability Purpose

$$Np = OOIP \cdot E_R$$

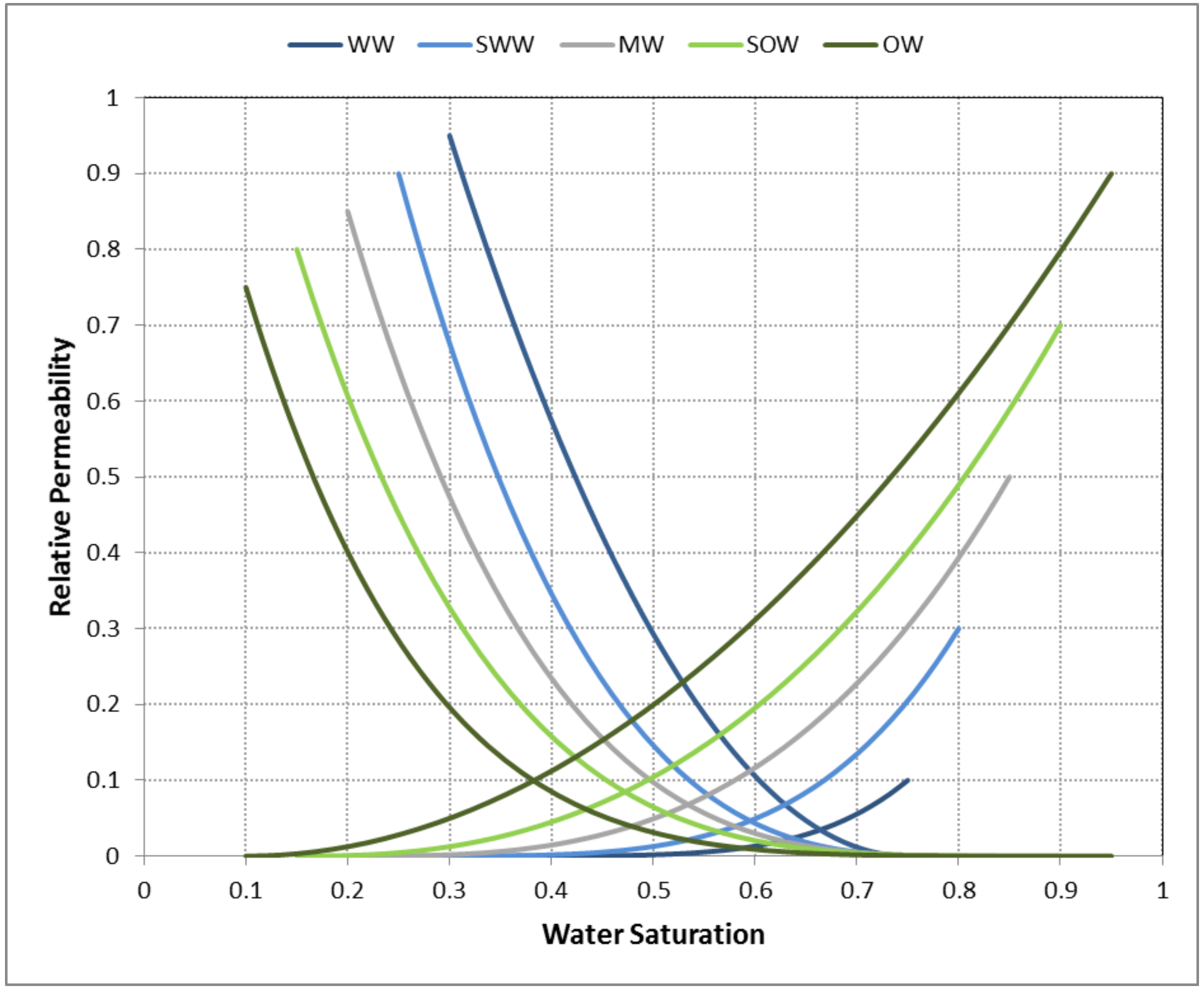
Np = Cumulative oil produced (STB)
OOIP = Original oil in place (STB)
E_R = Recovery Efficiency (fraction)

$$E_R = E_{PS} \cdot E_S \cdot E_D \cdot E_C$$

E_{PS} = **Microscopic sweep efficiency (fraction)** *(core analysis designed to provide this term)*
E_S = Macroscopic sweep efficiency (fraction) = Volumetric sweep = Areal · Vertical
E_D = Connected sweep efficiency (fraction)
E_C = Economic efficiency (fraction) *(important factor in considering production life and/or EOR potential)*

Relative Permeability – Influencing Factors

Relative Permeability – correct wetting is essential



WW – Water wet
SWW – Slightly water wet
MW – Mixed wet
SOW – Slightly oil wet
OW – Oil wet

- Relative permeability also controlled by other factors
  - Heterogeneity, grain/pore size, saturation hysteresis

Relative Permeability – Influencing Factors

Test States

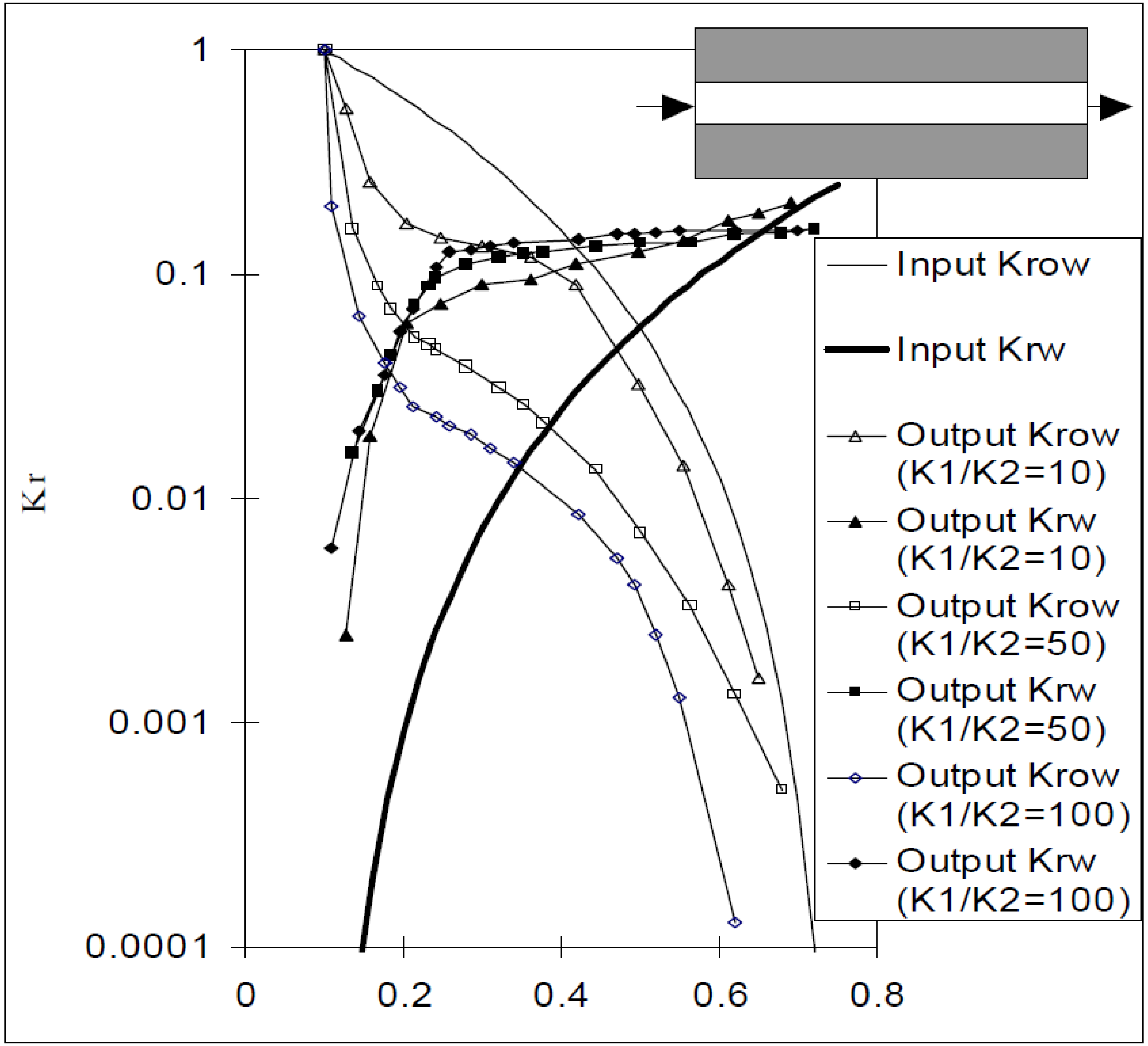
- "Fresh" or "Preserved" State
  - tested "as is" (no cleaning)
  - often too oil wet (e.g OBM, long term storage)
  - "Native" state term also used (defines "bland" mud)
- "Cleaned" State
  - cleaned (soxhlet or miscible flush)
  - water-wet expected (but could be oil-wet from soxhlet)
- "Restored" State (reservoir-appropriate wettability)
  - native wettability restored
  - saturate in crude oil – live oil or STO
    - if GOR low (< 200 scf/bbl) can use dead crude ageing (cheaper)
    - if GOR high must use live crude ageing (expensive)
  - age in oil at P & T to restore native wettability

Relative Permeability – Influencing Factors

SOCIETY OF
CORE ANALYSTS

Heterogeneity effect

- Heterogeneity has a large impact on relative permeability
- Samples should be homogeneous – representing microscopic sweep of a specific layer

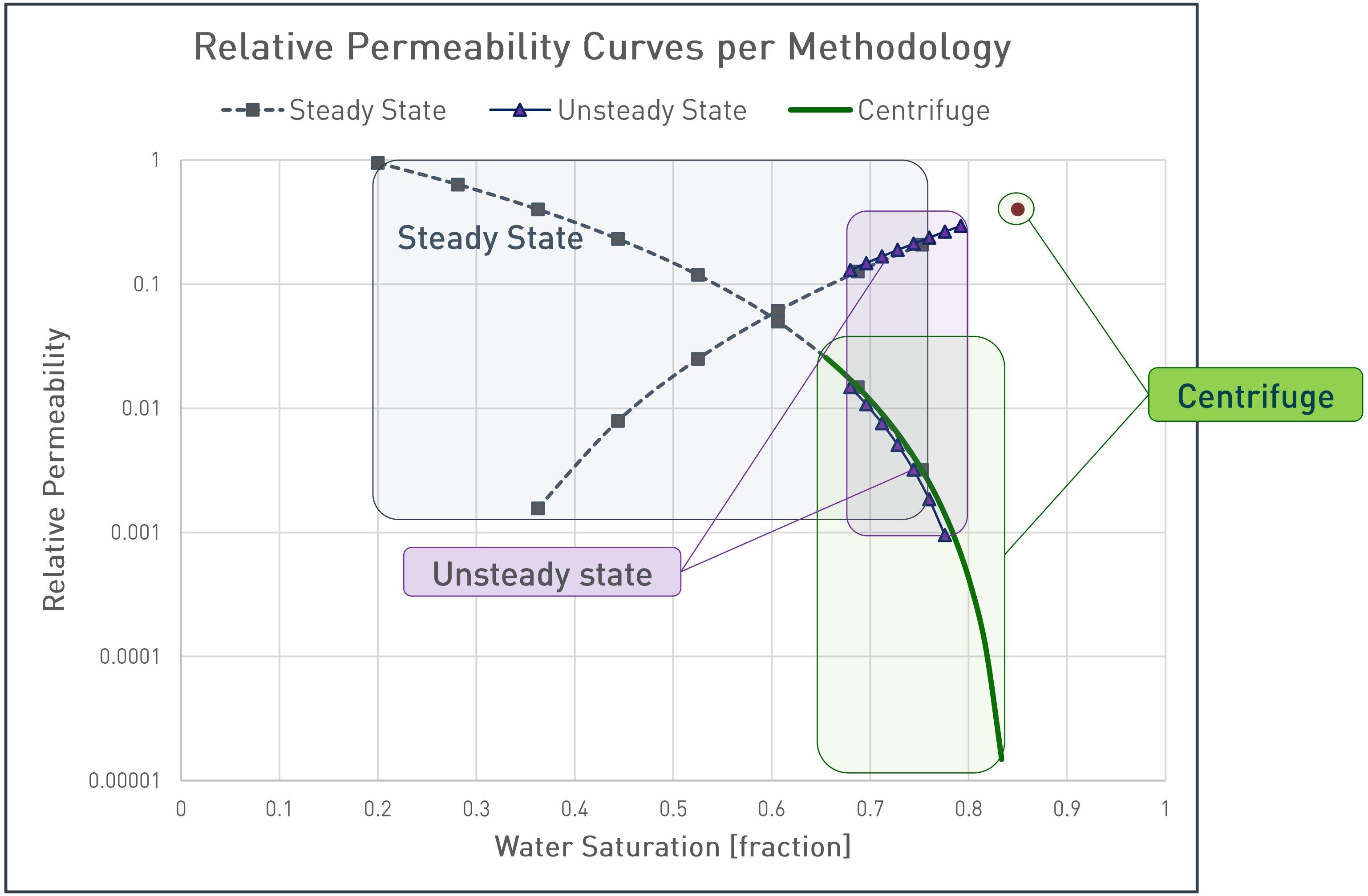


Hamon, Roy: SCA2000-23

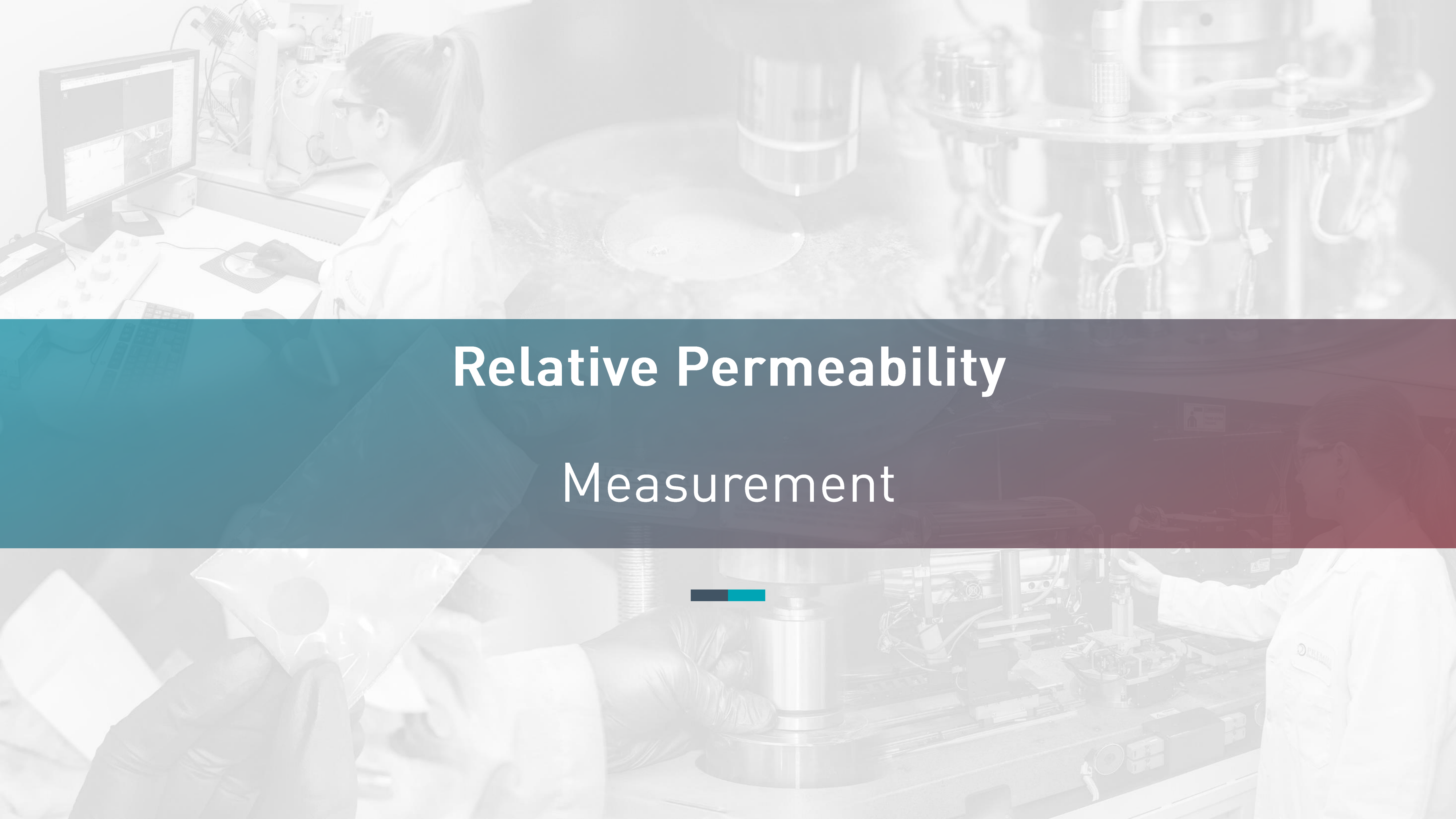
Relative Permeability – Influencing Factors

Method Sensitivity

- Unsteady state
  - Frontal displacement
  - Limited S range
  - Limited Kr (10^{-3})
  - Not Sor
- Steady state
  - No flood front
  - Full S range
  - Limited Kr (10^{-3})
  - Not Sor
- Centrifuge
  - Gravity driven
  - Limited S range
  - Only one kr curve
  - Low kr defined (10^{-6} – 10^{-8})
  - Near Sor?



Per Ebeltoft



Relative Permeability

Measurement

Relative Permeability – How is it measured?

SOCIETY OF CORE ANALYSTS

Unsteady State Method

- Saturate – formation water
- Water permeability
- Desaturate to Swi – porous plate (or centrifuge)

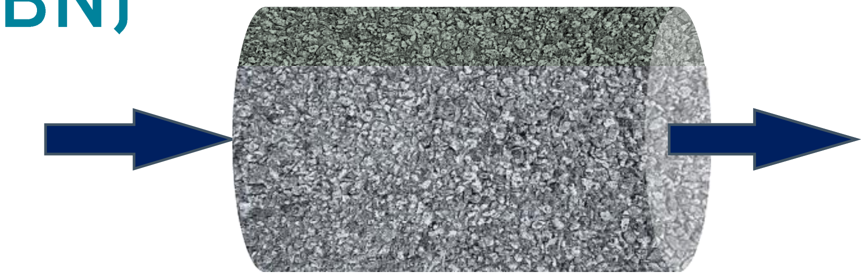
NOT FRESH STATE ANALYSIS

- Effective ko at Swi
- Ageing – wetting restoration
- Effective ko at Swi

ONLY RESTORED STATE ANALYSIS

- Waterflood
  - Incremental and total oil recovery
  - Intermediate relative permeability (JBN)
- Effective kw at Sor

$$\left(\frac{\mu_o}{\mu_w}\right)_{lab} >> \left(\frac{\mu_o}{\mu_w}\right)_{res}$$

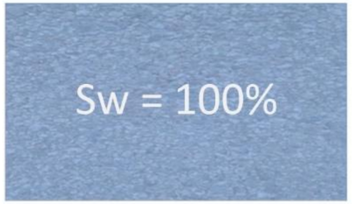


Relative Permeability – How is it measured?

Unsteady State Process

Brine saturated core

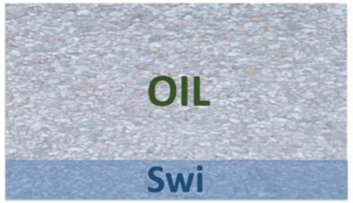
1)



Brine permeability
kw

Desaturation to Swi with oil

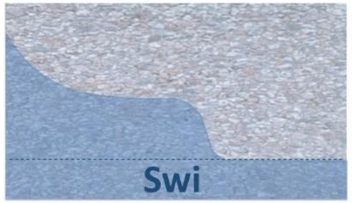
2)



Effective oil permeability
ko@Swi

Initial waterflood stages, before breakthrough (only oil produced)

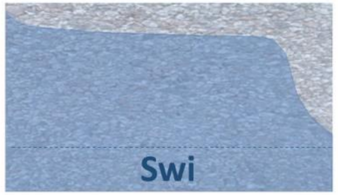
3)



Two-phase flow

Water breakthrough

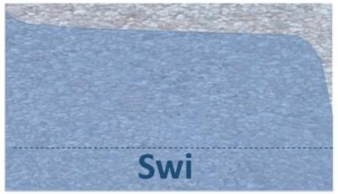
4)



kw' and ko'

Continued waterflood (both oil and water produced)

5)

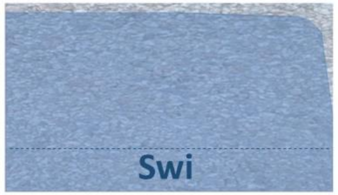


kw' and ko'

Two-phase flow

Waterflood enpoint – Residual oil saturation (only water produced)

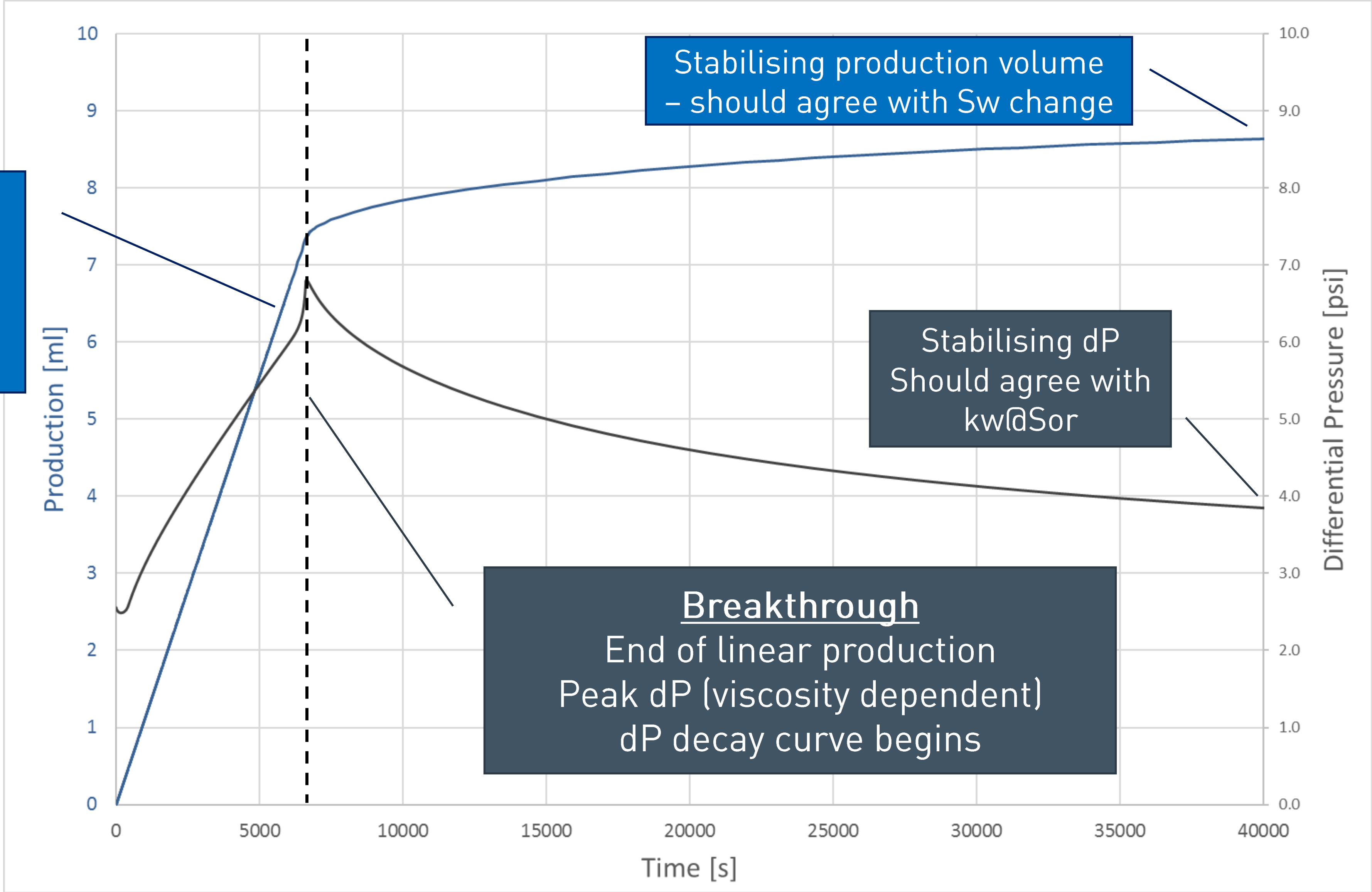
6)



Effective brine permeability
kw@Sro

Relative Permeability – How is it measured?

Expected Data



Pre-breakthrough
Linear production

Water PVI = Oil Np

Stabilising production volume
– should agree with Sw change

Stabilising dP
Should agree with
kw@Sor

Breakthrough
End of linear production
Peak dP (viscosity dependent)
dP decay curve begins

Relative Permeability – How is it measured?

Saturation determination

- Gravimetrics (not recommended)
- Volumetrics
  - PVT sight cells
  - acoustic separators
  - test tubes and flasks
- Non-Invasive (In Situ) Saturation Monitoring e.g. ISSM
  - radioactive & magnetic methods - X ray (CT – 3D), gamma ray, NMR (3D)
  - resistivity monitoring
- Dean-Stark extraction
  - final water saturation at end of test
- Karl Fischer titration
  - Solvent effluent from injection cleaning
- Dispersion (miscible tracer) flooding

Relative Permeability – How is it measured?

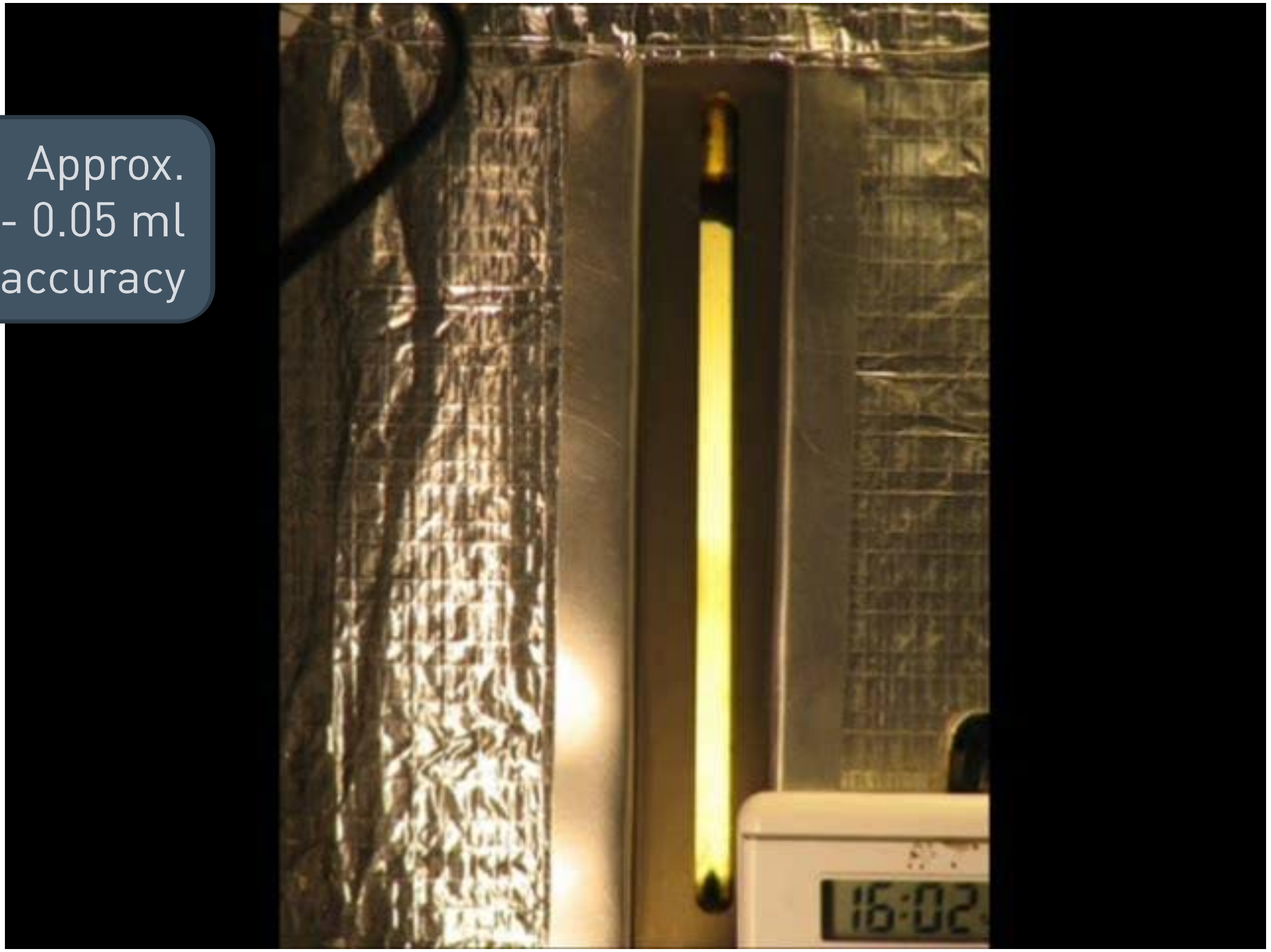
Saturation determination

- Volumetrics
  - PVT sight cells
  - acoustic separators
  - test tubes and flasks

Approx. 0.03 - 0.05 ml accuracy

$$Sw = Sw_{init} \overset{imb}{\underset{drn}{\pm}} \frac{V_{prod}}{V_p}$$

Sw_{init} = initial water saturation
V_{prod} = production volume
V_p = pore volume

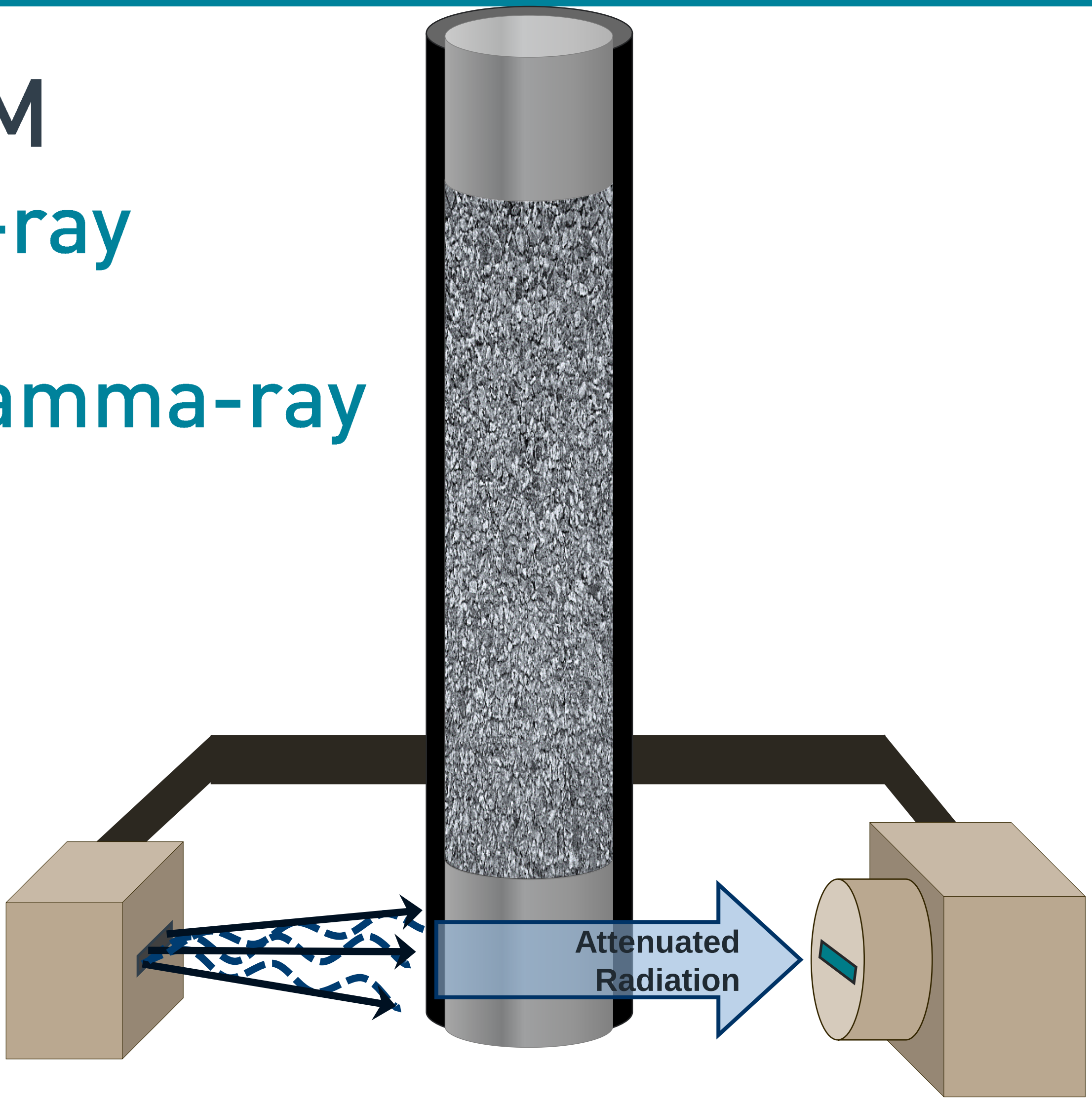


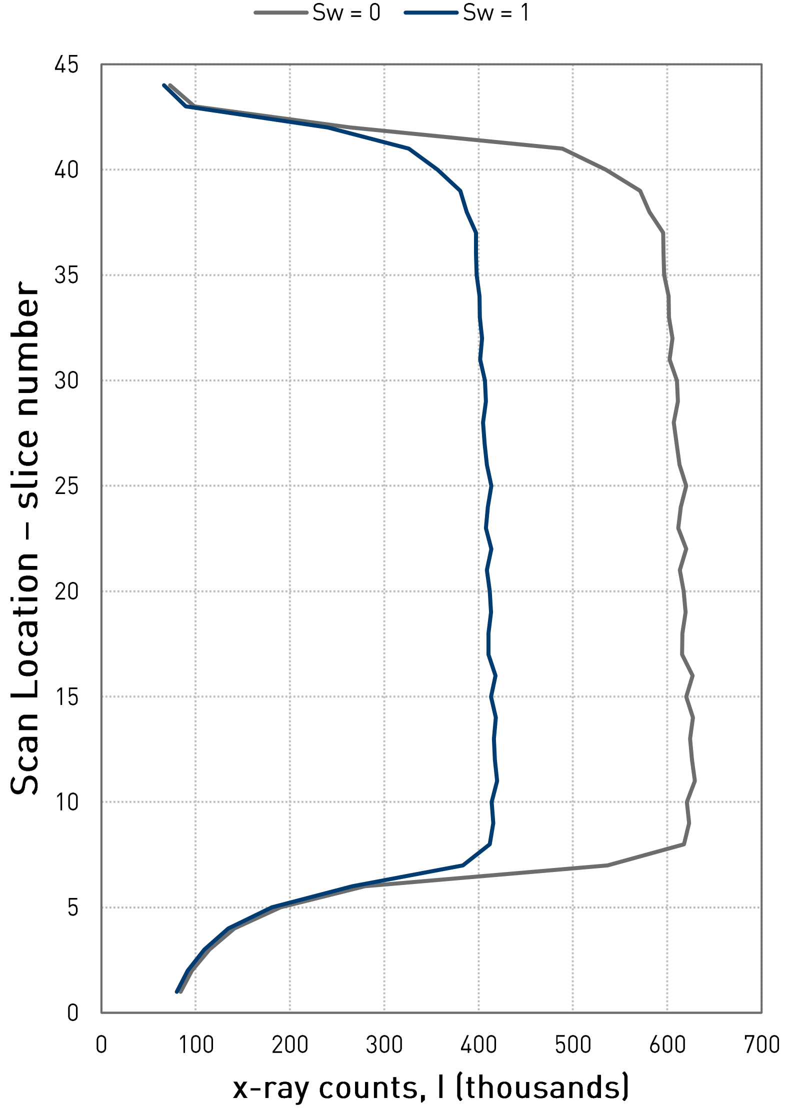
Relative Permeability – How is it measured?

ISSM – *In-Situ* Saturation Monitoring

- ISSM
  - X-ray

    or
  - gamma-ray





Relative Permeability – How is it measured?

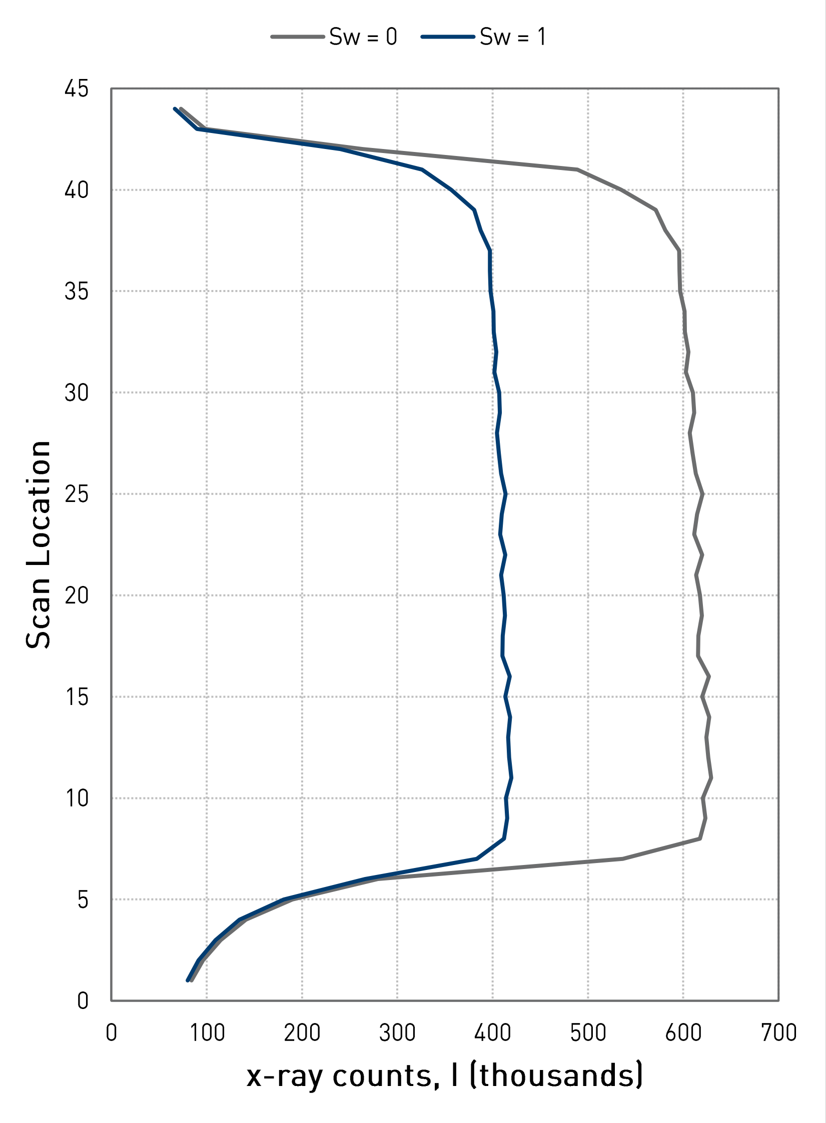
ISSM calibration

- Saturation calculated using Beer-Lambert Law

$$I = I_0\, e^{-\mu x}$$

- Assuming rock component is constant, system is calibrated between Sw = 0 and Sw = 1

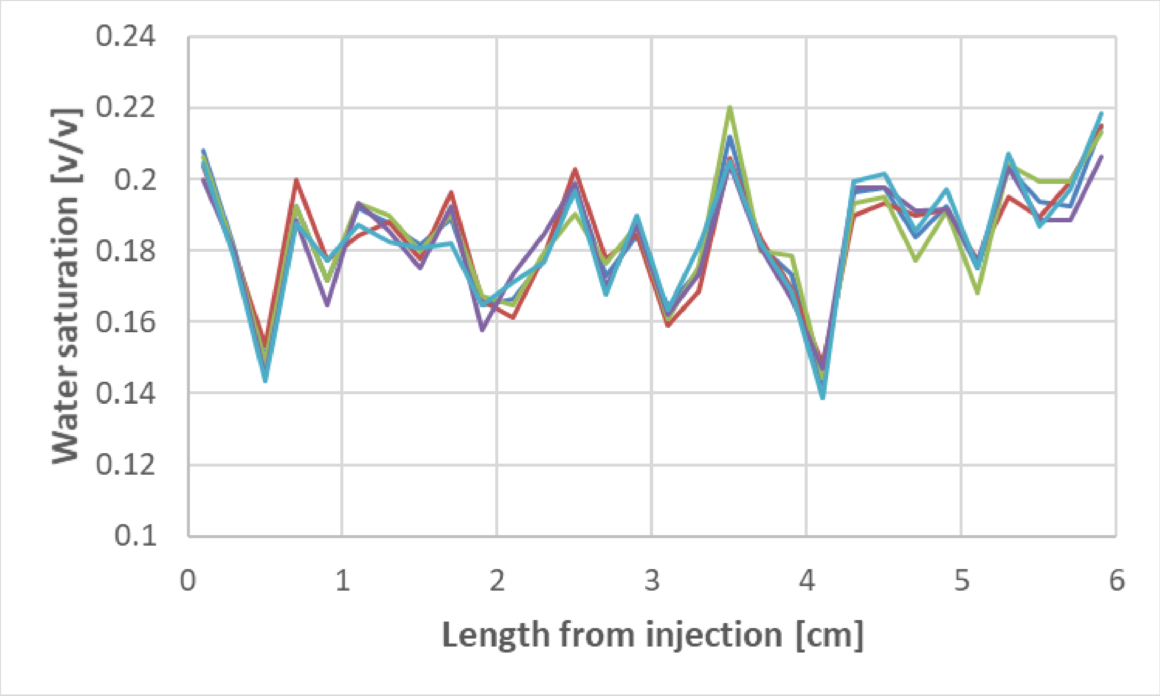
$$Sw = \frac{\ln(I) - \ln(I_{So})}{\ln(I_{Sw}) - \ln(I_{So})} = \frac{\ln\left({}^{I}/_{I_{So}}\right)}{\ln\left({}^{I_{Sw}}/_{I_{So}}\right)}$$



Relative Permeability – How is it measured?

ISSM Accuracy

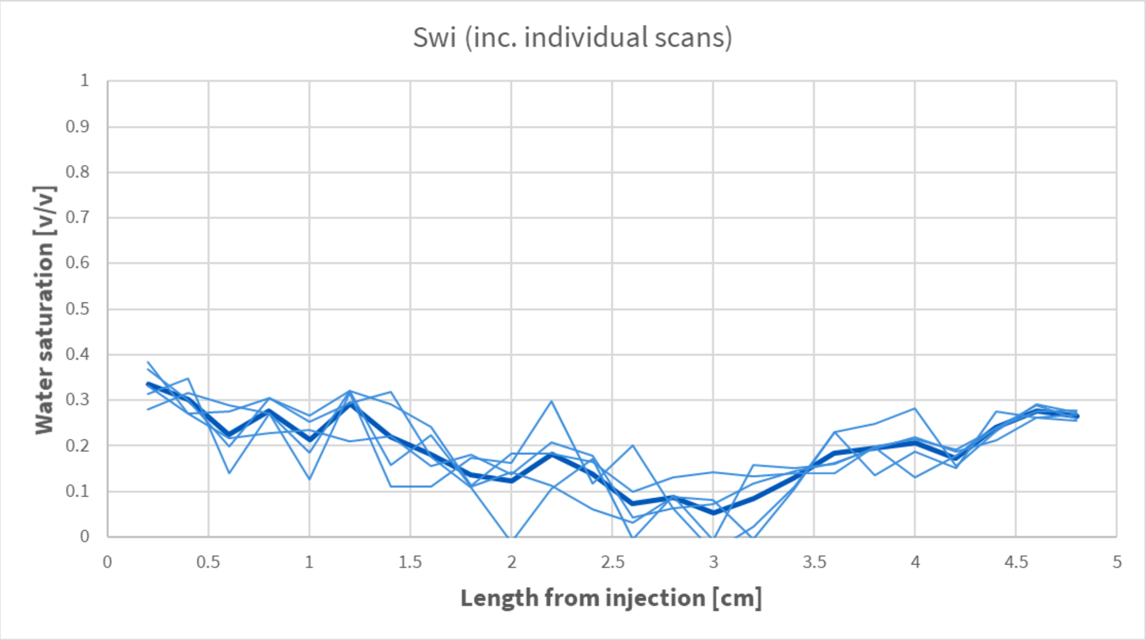
- ISSM claimed accuracy: ± 1 s.u. (some companies ± 2 s.u.)
- Accuracy dependent on various factors:
  - Test conditions – pressure or temperature variance
  - Radiation source stability
    - Radioactive decay, Power variance, etc
  - Core heterogeneity
  - Core / motor location accuracy
  - Constant core properties
  - Constant fluid properties during test
  - Full cleaning/saturation during calibration
  - **Number of counts obtained (Should be controlled per test)**



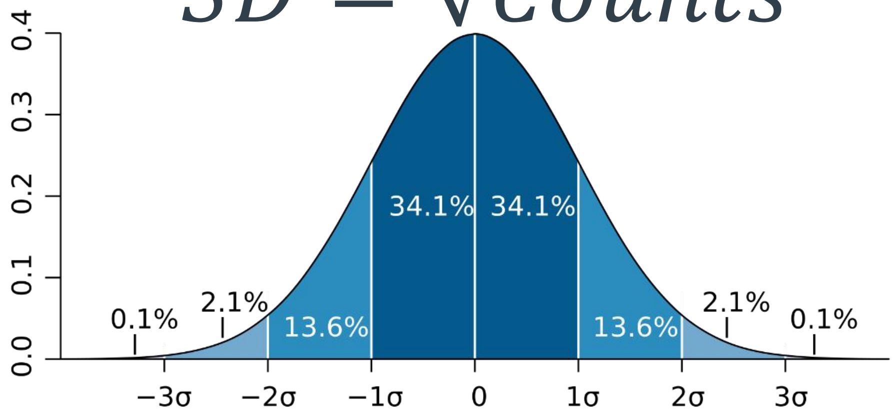
Relative Permeability – How is it measured?

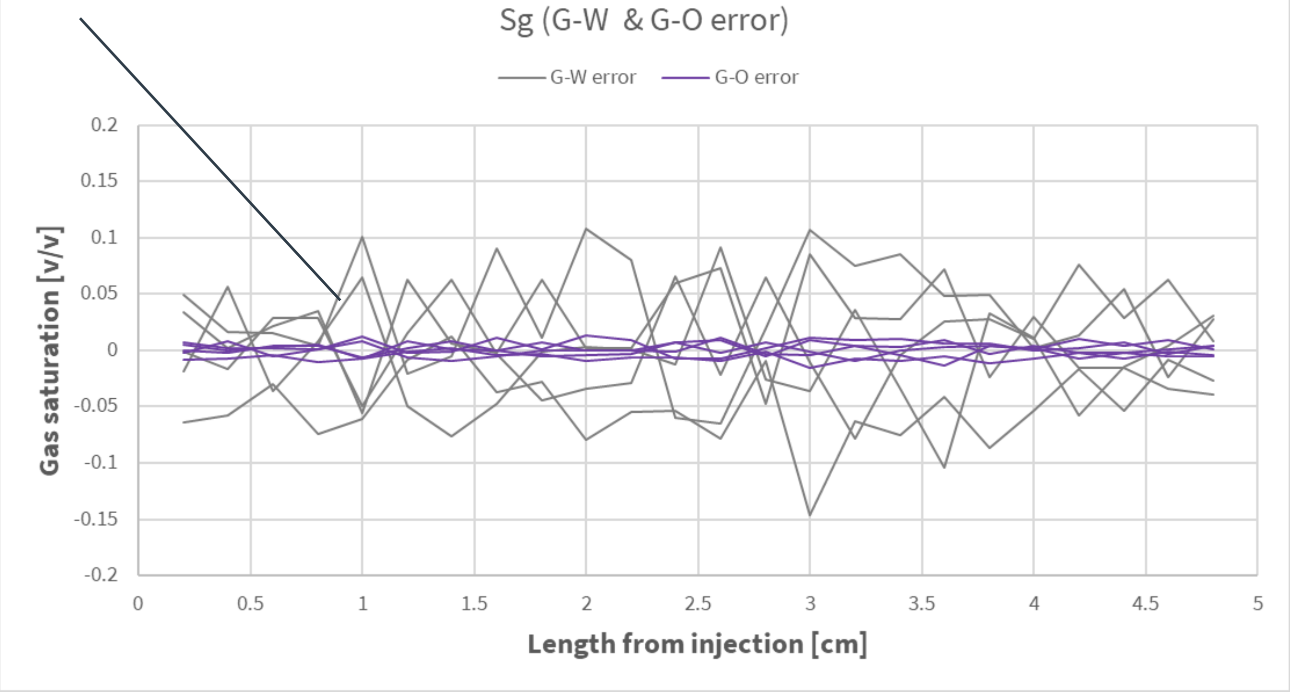
ISSM Uncertainty

- Saturation error should be < ± 1 s.u.
- 3x SD captures the entire expected Gaussian error.
- Increasing total counts decreases overall error
- This should be used to calculate total counts required to keep error below desired ± 1 s.u.
- Grey scans below show uncontrolled test errors (10 – 15 s.u. errors)
- Purple scans show correctly controlled test errors



$$SD = \sqrt{Counts}$$





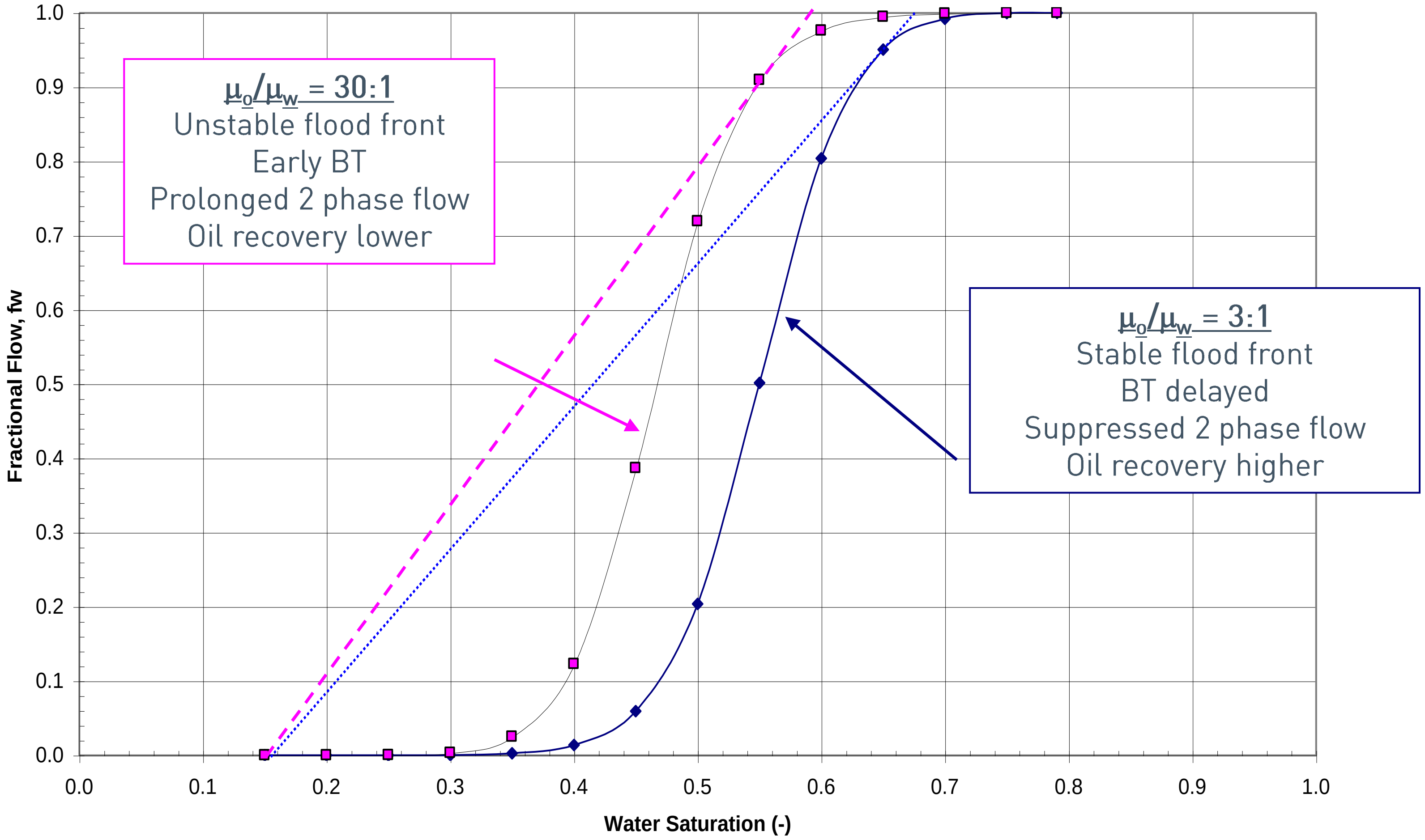
Unsteady-State

SOCIETY OF CORE ANALYSTS

- Rel perm calculations require
  - fractional flow data at core outlet (JBN)
  - pressure data versus water injected
- Old method used high oil viscosity ratio
  - promote viscous fingering
  - provide fractional flow data after BT
  - allow calculation of rel perms
- Waterflood (matched viscosity ratio)
  - little or no oil after BT (wettability dependent)
  - little or no fractional flow (no rel perms)
  - Maybe end points only

$$f_w = \frac{1}{1 + \frac{k_{ro}}{k_{rw}} \cdot \frac{\mu_w}{\mu_o}}$$

Effect of Adverse Viscosity Ratio



μ_o/μ_w = 30:1
Unstable flood front
Early BT
Prolonged 2 phase flow
Oil recovery lower

μ_o/μ_w = 3:1
Stable flood front
BT delayed
Suppressed 2 phase flow
Oil recovery higher

Relative Permeability – How is it measured?

Unsteady state method

- Johnson, Bossler, Nauman (JBN)
  - Based on Buckley-Leverett/Welge

$$f_w = \frac{1}{1 + \frac{k_{ro}}{k_{rw}} \cdot \frac{\mu_w}{\mu_o}}$$

  - Swa = average (plug) Sw
  - W = PV water injected
  - $fw_2 = 1 - fo_2$

$$\frac{dS_{wa}}{dW} = f_{o2}$$

Injectivity Ratio

Waterflood rate, q

$$I_r = \frac{\Delta p_{t=0}}{\Delta p_{t=i}}$$

$$\frac{d\left(\frac{1}{WI_r}\right)}{d\left(\frac{1}{W}\right)} = \frac{f_{o2}}{k_{ro2}}$$

Unsteady-State Tests

- Advantages
  - appropriate Buckley-Leverett “shock-front”
  - reservoir flow rates possible
  - fast and low throughput (fines)
- Disadvantages
  - capillary boundary effects at lower rates
  - complex interpretation
  - Only post BT data are used for rel perm calculations
  - Sw range restricted if matched viscosities

Relative Permeability – How is it measured?

SOCIETY OF CORE ANALYSTS

Steady State Method

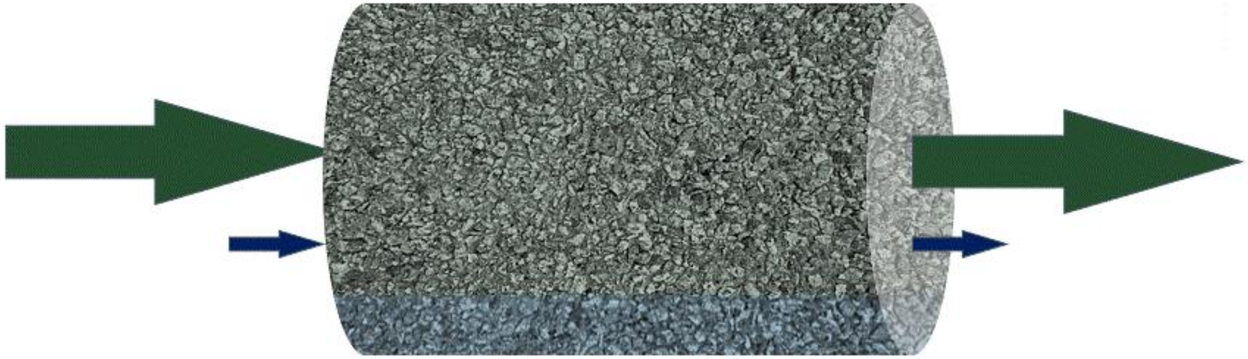
- Saturate – formation water
- Water permeability
- Desaturate to Swi – porous plate (or centrifuge)

NOT FRESH STATE ANALYSIS

- Effective ko at Swi
- Ageing – wetting restoration
- Effective ko at Swi

ONLY RESTORED STATE ANALYSIS

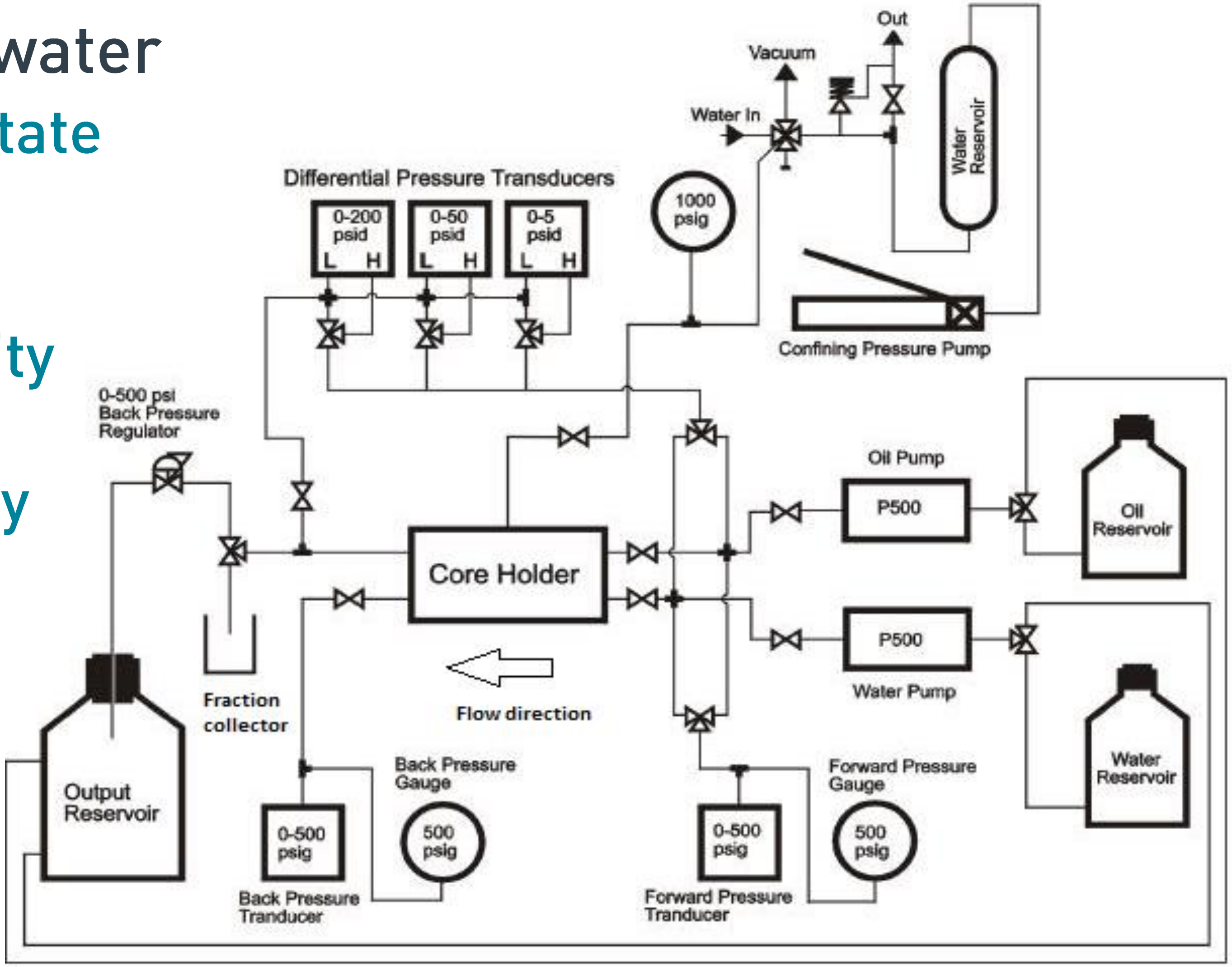
- Simultaneous Injection Water/Oil
  - Controlled fractional flow
- Effective kw at Sor



Relative Permeability – How is it measured?

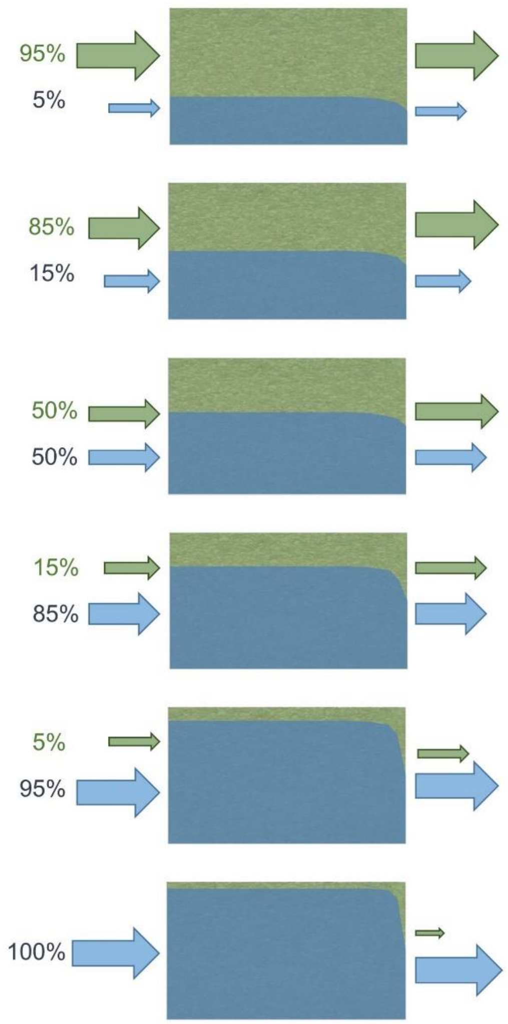
Steady State Method

- Simultaneous injection oil and water
  - Monitor DP & Sw until steady state
  - Determine Sw at steady state conditions
  - Determine effective permeability (Darcy)
  - Determine relative permeability (divide by k_{ref})
  - Repeat for different fw



Relative Permeability – How is it measured?

Example SS test parameters



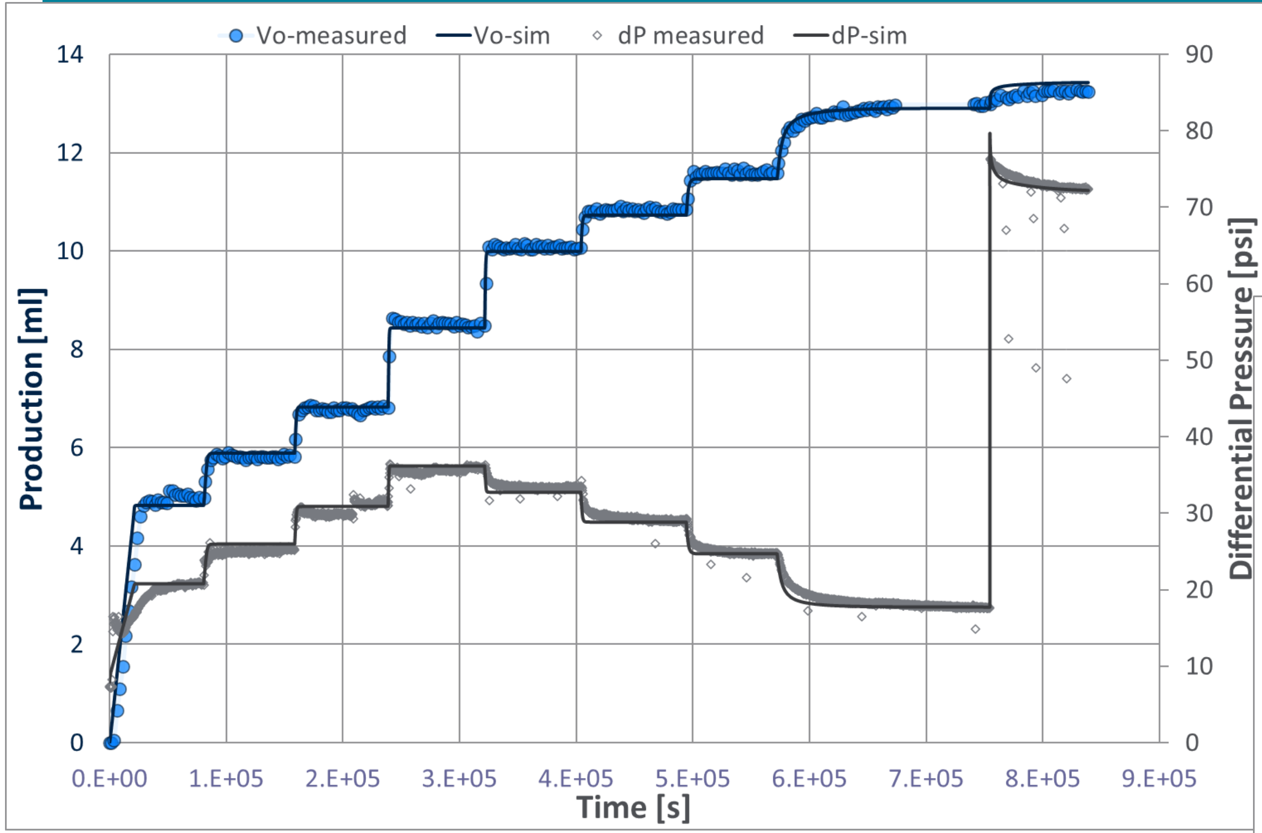
Summary

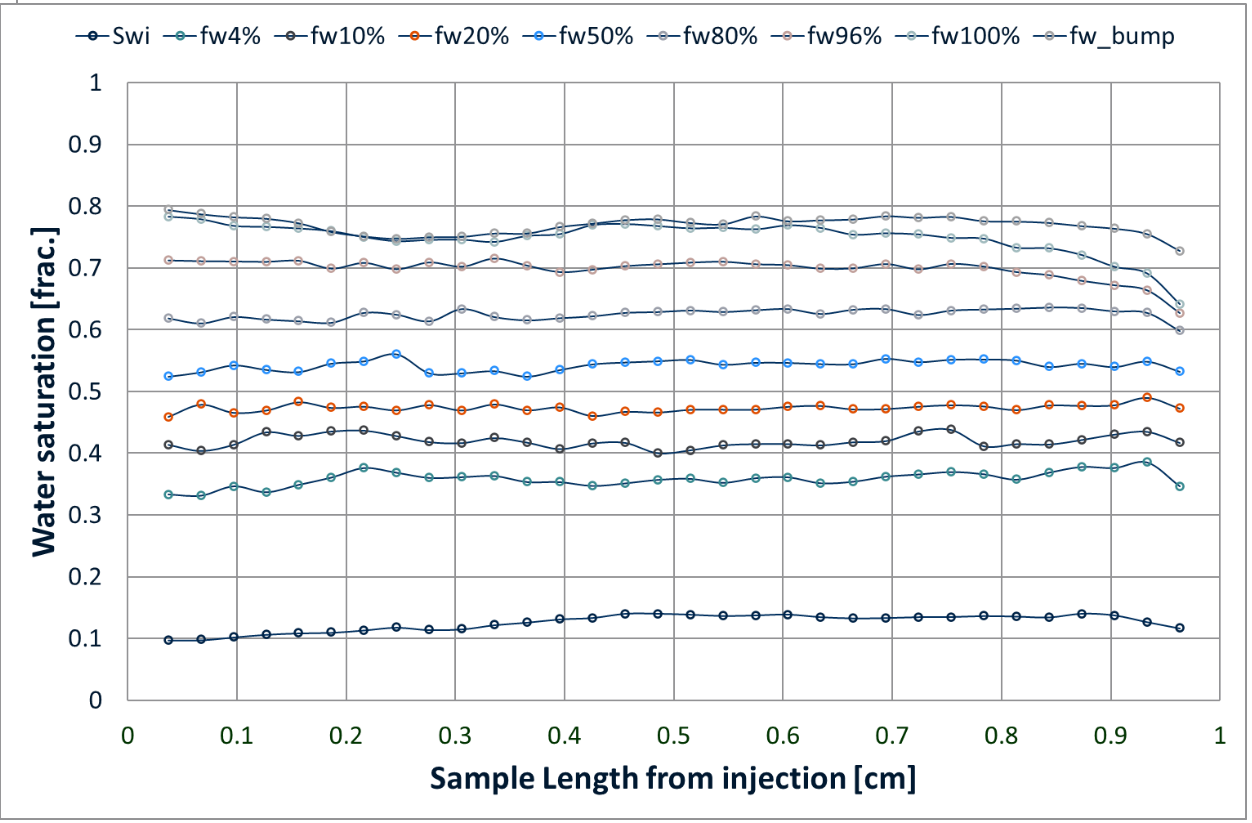
100% oil:	ko@Swi
Ratio 1:	ko’ & kw’ @ Sw[1]
Ratio 2:	ko’ & kw’ @ Sw[2]
…	…
…	…
Ratio n:	ko’ & kw’ @ Sw[n]
100% water	kw@Sro

Total flow rate	Water flow rate	Oil flow rate	Fractional water flow	Fractional oil flow	Test stage
Qt	Qw	Qo	fw	fo	
1.00	0.00	1.00	0.00	1.00	ko (Swi)
1.00	0.02	0.98	0.02	0.98	fw1
1.00	0.05	0.95	0.05	0.95	fw2
1.00	0.15	0.85	0.15	0.85	fw3
1.00	0.50	0.50	0.50	0.50	fw4
1.00	0.85	0.15	0.85	0.15	fw5
1.00	0.95	0.05	0.95	0.05	fw6
1.00	0.98	0.02	0.98	0.02	fw7
1.00	1.00	0.00	1.00	0.00	kw(Sor)

Relative Permeability – How is it measured?

Example Data





Relative Permeability – How is it measured?

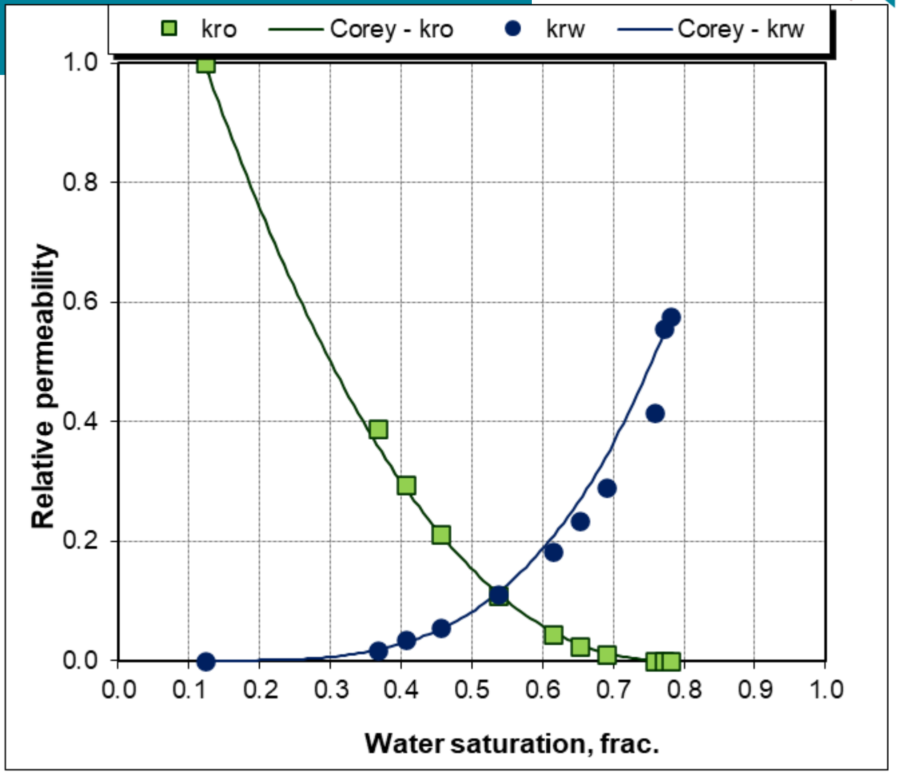
Example SS DAta

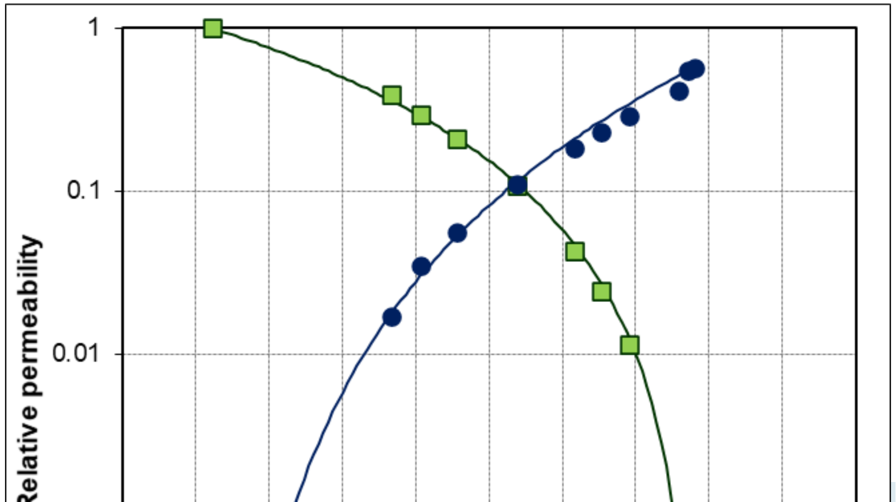
Imbibition Relative Permeability - Analytical

Oil (ml/min)	Brine (ml/min)	Brine (fw)	DP (kPa)	kw (mD)	ko (mD)	krw	kro	Sw γ attn. (frac)
0.371	0.000	0.000	52.6	0.0	2.5	0.000	1.000	0.122
0.356	0.014	0.038	129.7	0.04	1.0	0.017	0.389	0.366
0.333	0.035	0.096	160.2	0.1	0.7	0.035	0.295	0.407
0.296	0.070	0.192	198.3	0.1	0.5	0.056	0.212	0.456
0.189	0.173	0.478	246.2	0.3	0.3	0.110	0.109	0.538
0.074	0.282	0.792	243.4	0.5	0.1	0.182	0.043	0.615
0.037	0.317	0.895	214.5	0.6	0.1	0.233	0.025	0.653
0.015	0.338	0.958	184.6	0.7	0.0	0.289	0.011	0.690
0.000	0.352	1.000	133.5	1.04	0.0	0.416	0.000	0.758
0.000	1.762	1.000	499.2	1.39	0.0	0.556	0.000	0.771
0.000	3.525	1.000	963.8	1.44	0.0	0.576	0.000	0.781

$$k = \frac{q \cdot \mu \cdot L}{dP \cdot A}$$

Premier COREX



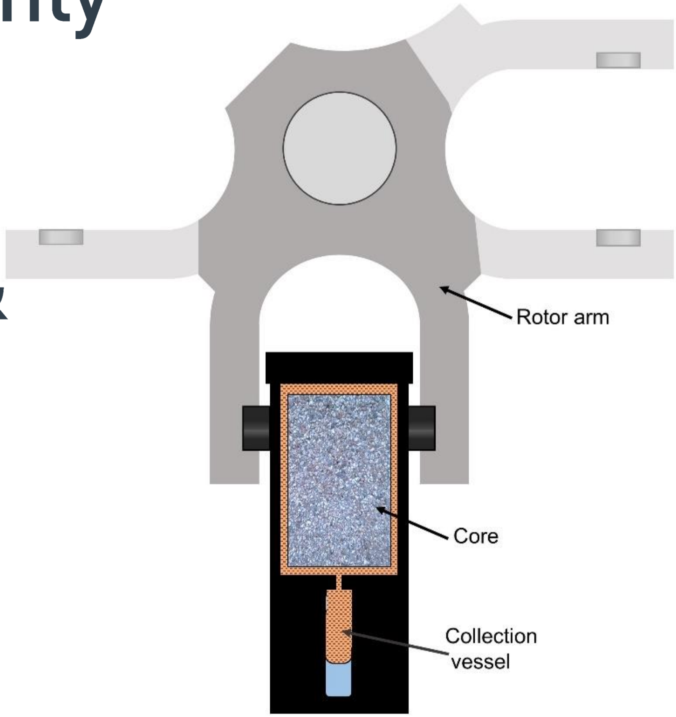


Relative Permeability – How is it measured?

SOCIETY OF CORE ANALYSTS

Centrifuge Method

- Displaced phase relative permeability only
  - imbibition – oil displaced – kro
  - drainage – water displaced – krw
- Tests at ambient or elevated pressure & temperature
  - synthetic fluids or stock tank oil
- Centrifuge spun at single speed
  - pressure differential across plug displaces oil
  - oil production monitored versus time
  - interpretation based on Hagoort
  - Simulation should be used



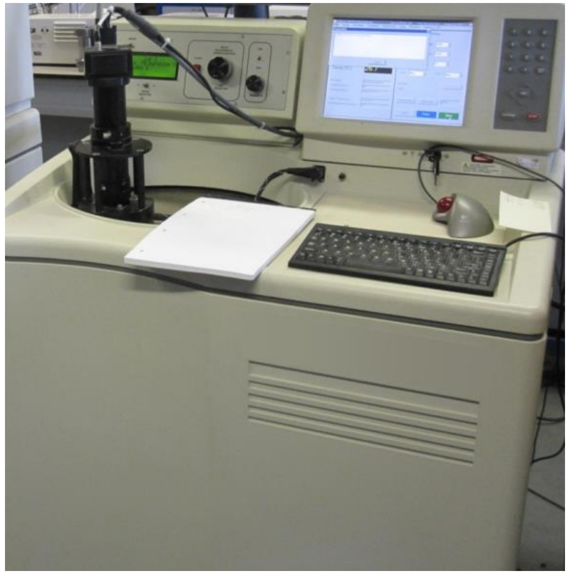
$$kro = \frac{1109 q_o \mu_o}{Ko' A(\rho_w - \rho_o) g}$$

$$g = 0.00001117 \omega^2 r$$

Relative Permeability – How is it measured?

Centrifuge Method

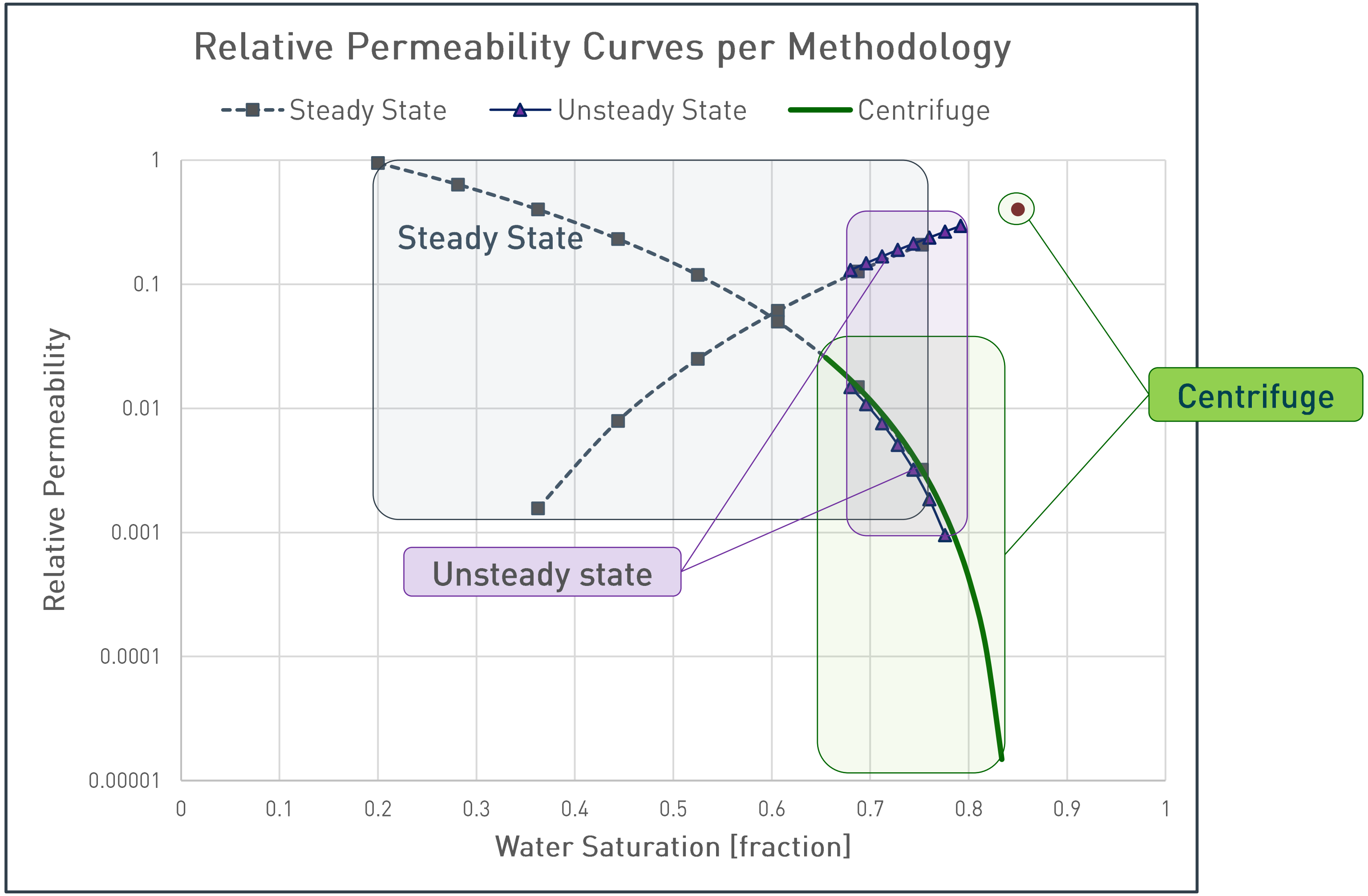
- Advantages
  - Large pressure difference created without instability
  - Large Δp reduces end effect
  - Large Δp may achieve ultimate residual saturation
  - Kro at Sro "tail"
  - Kro achieved rapidly
- Limitations
  - Displacing phase kr undefined
  - Limited pressure and temperature (if important)
    - tests can be performed on restored-state core but with synthetic fluids
  - End effects still present but reduced



Relative Permeability – How is it measured?

Method Sensitivity

- Unsteady state → limited definition & not Sor
- Steady state → Full curve range except Sor
- Centrifuge → defines Sor, only one kr curve



Relative Permeability – How is it measured?

USS vs SS vs Centrifuge

	USS	SS	Centrifuge
Fresh state	🟩	🟩	🟩
Clean state	🟩	🟩	🟩
Restored state	🟩	🟩	🟩
Elevated pressure	🟩	🟩	🟧
Elevated temperature	🟩	🟩	🟧
Live oil /gas	🟩	🟩	
Water-oil	🟩	🟩	🟩🟥
Oil-water	🟩	🟩	🟩🟥
Gas-water	🟩	🟩	🟩🟥
Water-gas	🟩	🟩	
Gas-oil	🟩	🟩	🟩🟥
Oil-gas	🟩	🟩	

Relative Permeability – How is it measured?

USS vs SS vs Centrifuge

	USS	SS	Centrifuge
Shockfront	Realistic	None	Gravity driven
Endpoints	Not Sor	Not Sor	Sor possible
Saturation calculation	Easy volumetric	Requires ISSM	Automated log
Reservoir flow rate	Possible	N/A	N/A
Potential damage	Limited	Maybe issues	Structural?
Test time	Rapid	Slow	Rapid
Relperm calculation	Differential extrapolation	Simple Darcy	Differential extrapolation
	Usually 10^{-3} limit	Usually 10^{-3} limit	10^{-6} - 10^{-9}
Heterogeneity impact	Poor	Better	Best
Flow instability	High rate	N/A	N/A
Capillary end effects	Rate dependent	Rate dependent	Reduced
Curve definition	Both fluids Limited S range	Both fluids Full range	Single fluid

Relative Permeability

Correlation

Relative Permeability Correlations

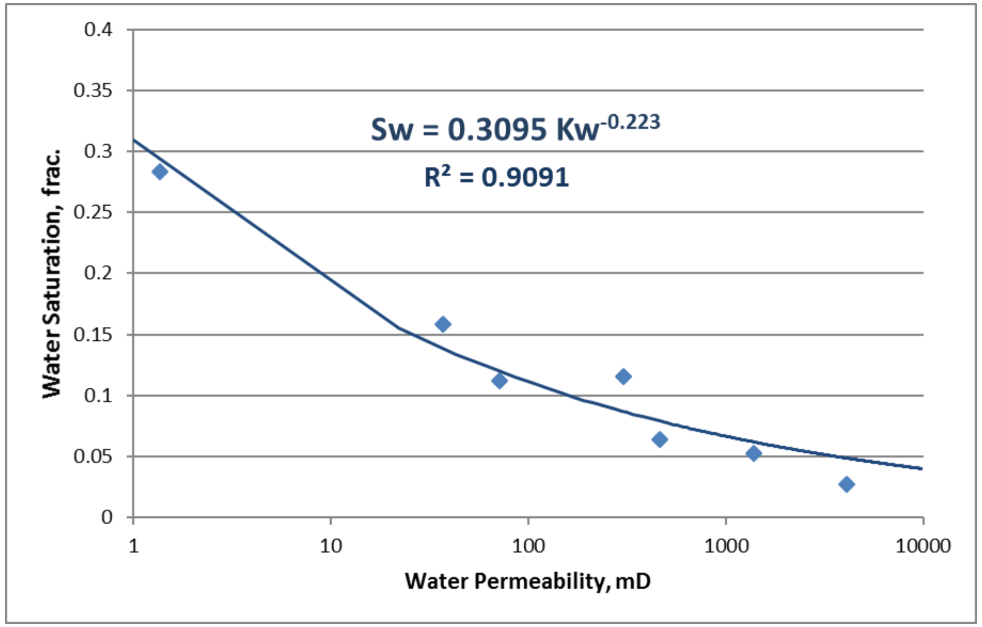
- Relative permeability is often statistically under-represented
- It is therefore sometimes difficult to determine reservoir controls on relative permeability parameters
- Dynamic models often employ only a single tabular relperm dataset, expected to describe the whole system

Relative Permeability Correlations

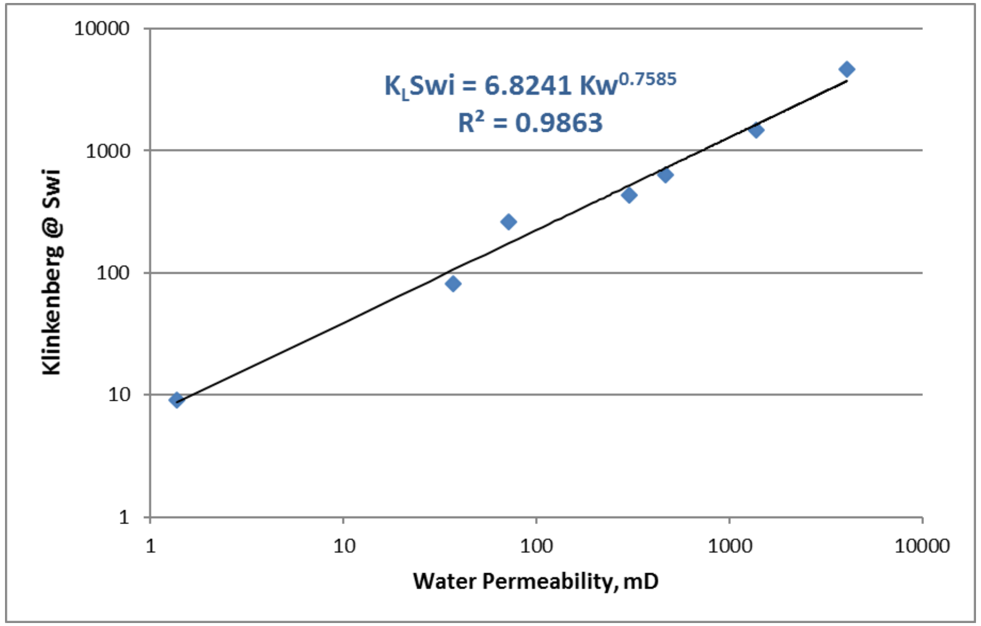
Endpoint & parameter correlations

- Attempt to determine relative permeability endpoints and model parameters as a function

S_{wi} versus k_w



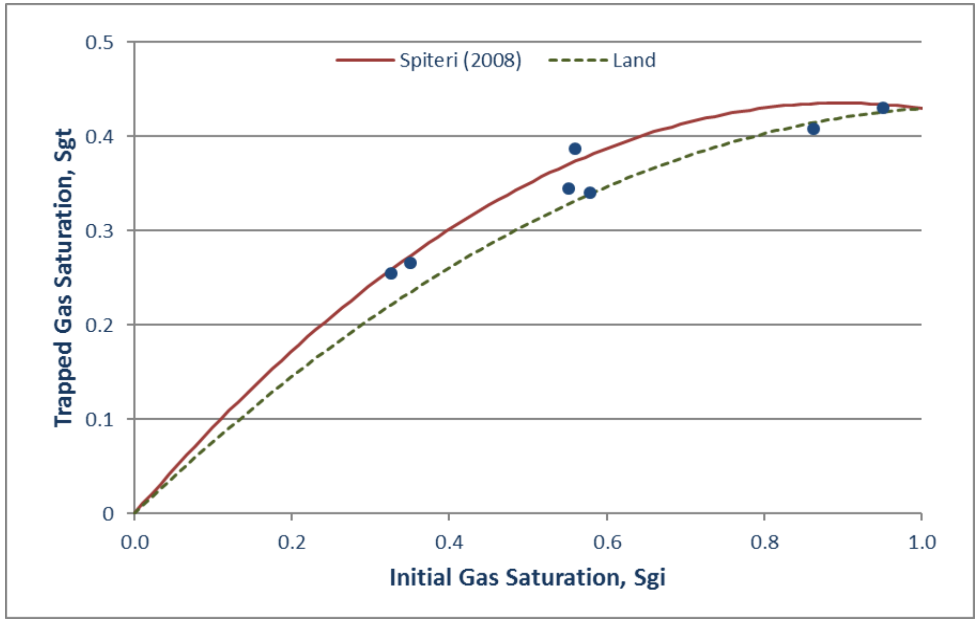
$k_L@S_{wi}$ versus k_w



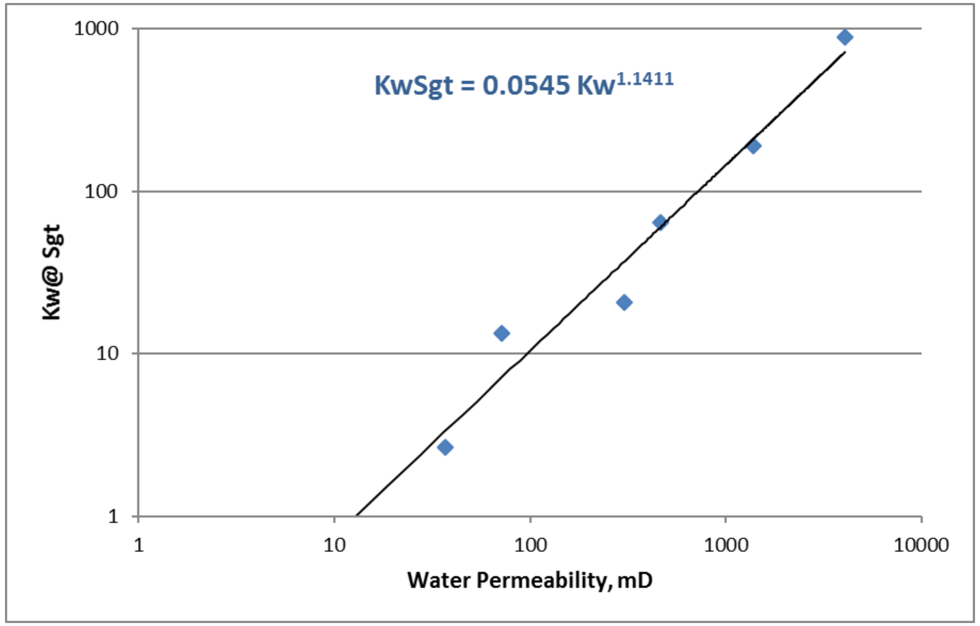
Relative Permeability Correlations

Endpoint correlations

S_{gt} versus S_{gi}

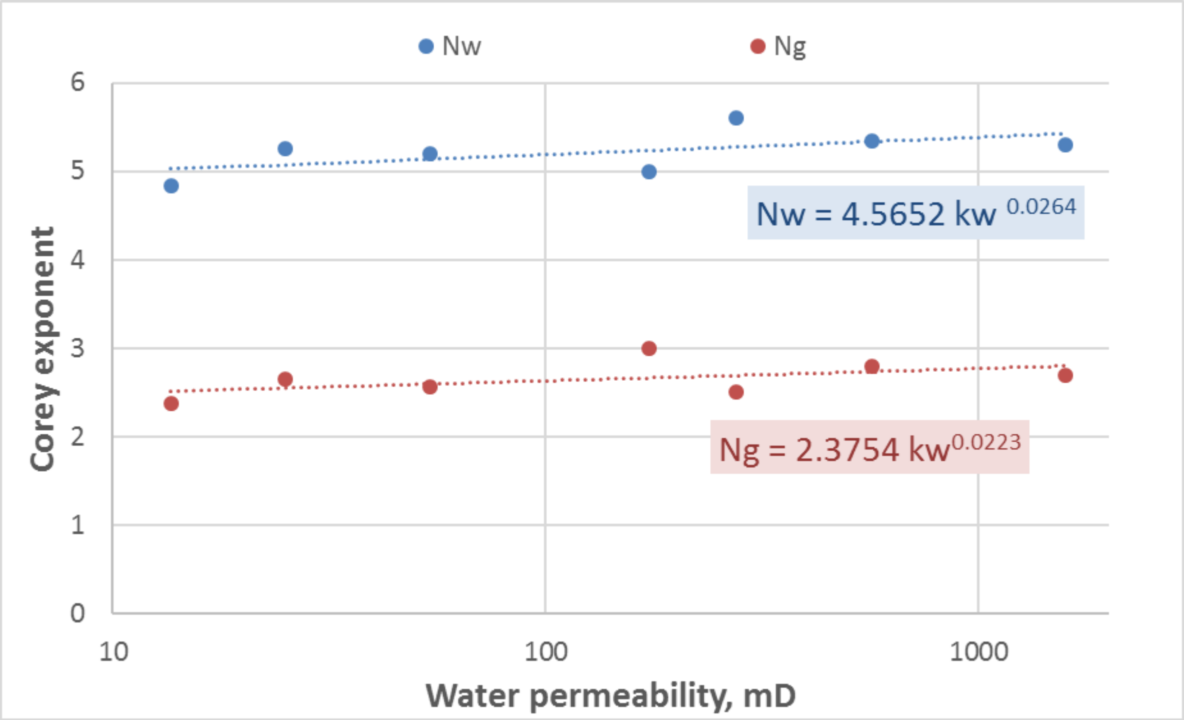


$k_w@S_{gt}$ versus k_w



Parameter correlations

N_w & N_g versus k_w



Relative Permeability Correlations

- Corey (Brooks-Corey)
- Sigmund & McCaffrey
- LET
- Chierici
- Burdine

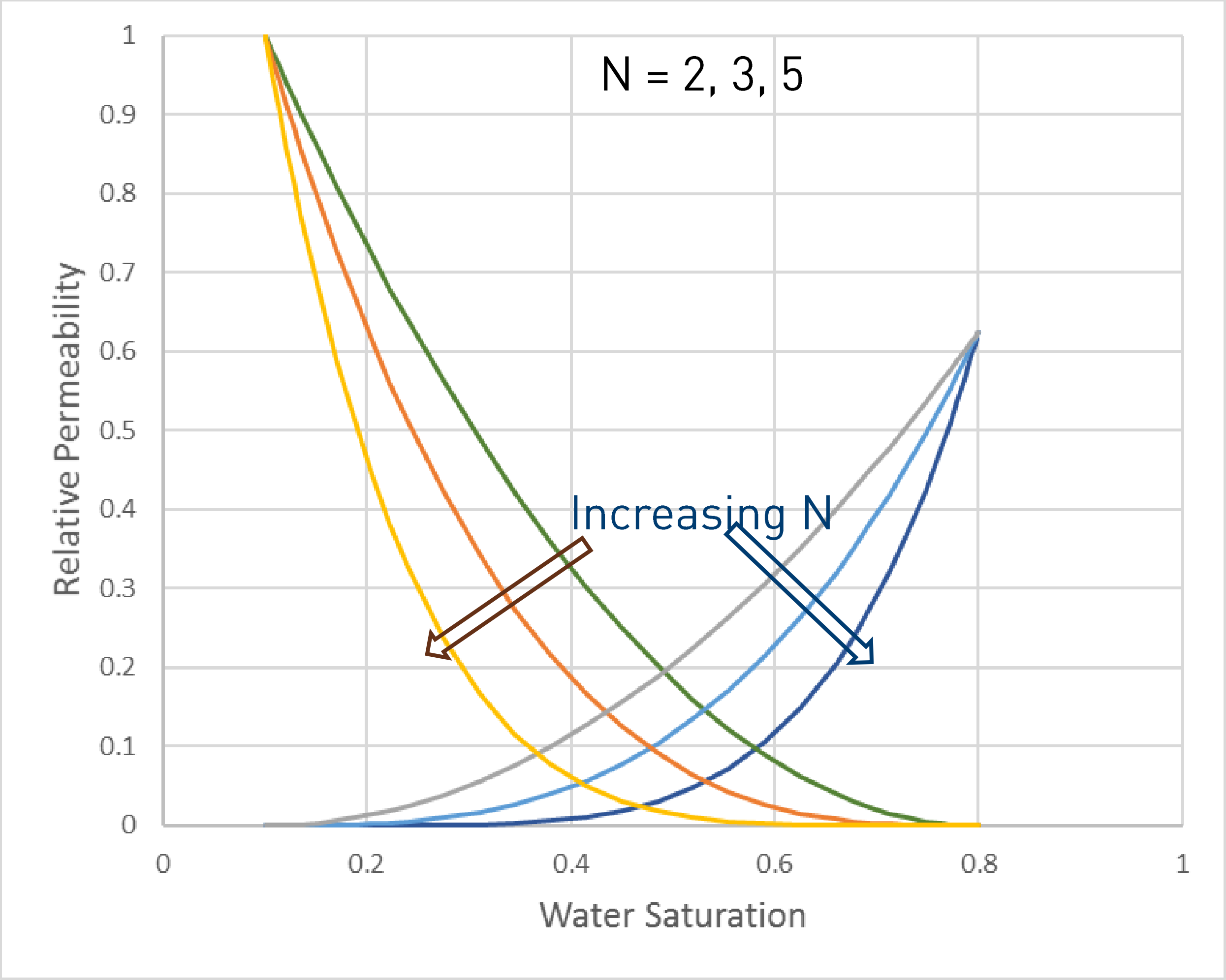
- Endpoint & parameter correlations
    - Reservoir characterisation for model input

Relative Permeability Correlations

Corey (Brooks-Corey)

$$k_{rw} = k^{*}_{rw}\,(S_{wn})^{Nw}$$

$$k_{ro} = k^{*}_{ro}\,(1 - S_{wn})^{No}$$

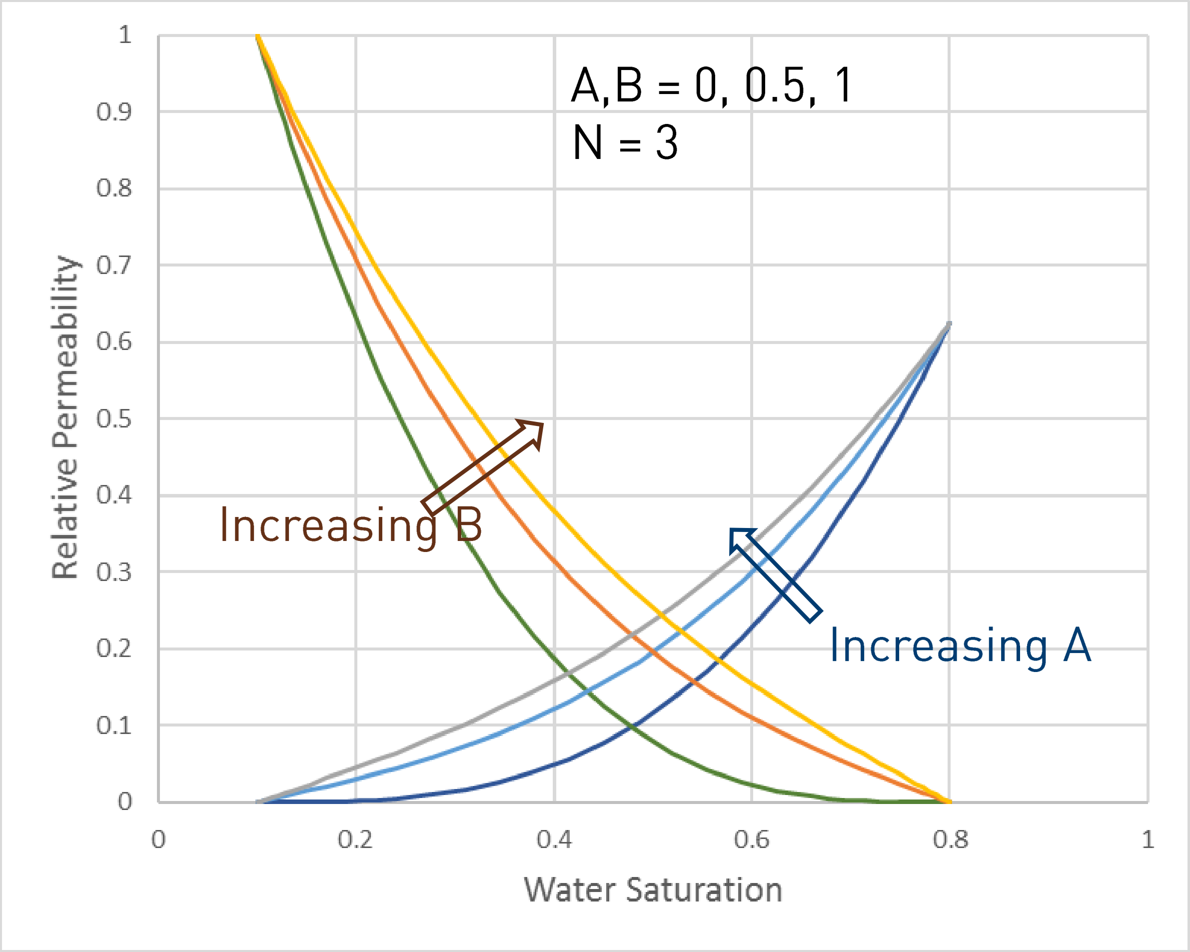


Relative Permeability Correlations

Sigmund & McCaffery

$$k_{rw} = k_{rw}^{*} \frac{(S_{wn})^{Nw} + A\, S_{wn}}{1+A}$$

$$k_{ro} = k_{ro}^{*} \frac{(1-S_{wn})^{No} + B(1-S_{wn})}{1+B}$$



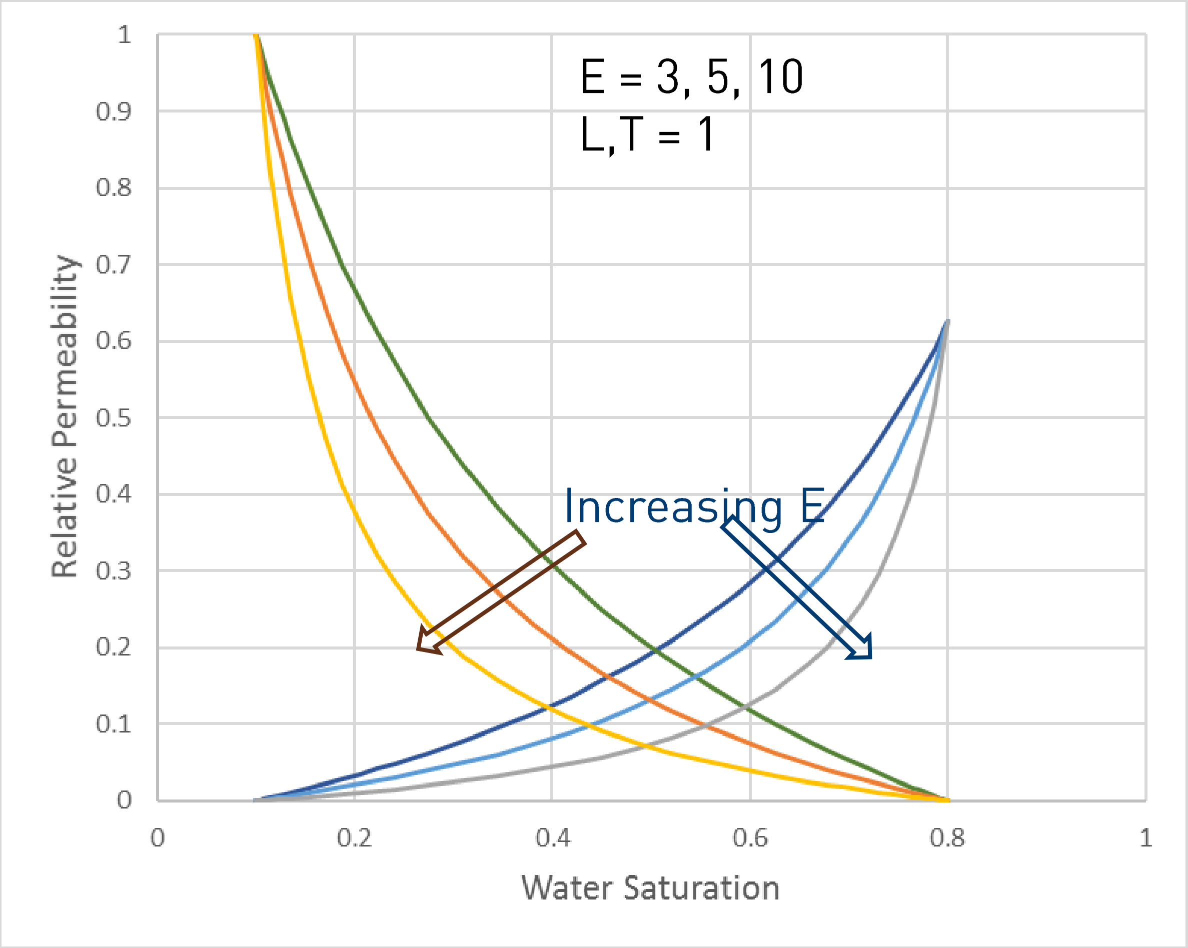
Relative Permeability Correlations

SOCIETY OF CORE ANALYSTS

LET

$$k_{rw} = k_{rw}^{*} \frac{(S_{wn})^{Lw}}{(S_{wn})^{Lw} + E_w(1-S_{wn})^{Tw}}$$

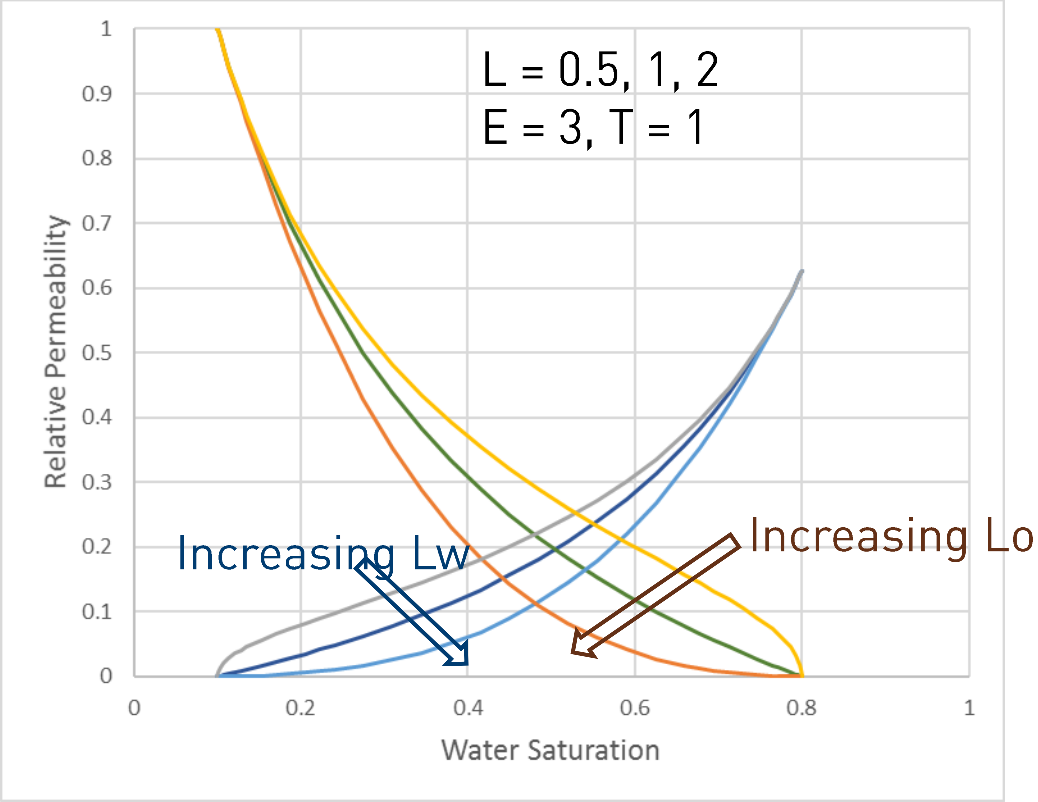
$$k_{ro} = k_{ro}^{*} \frac{(1-S_{wn})^{Lo}}{(1-S_{wn})^{Lo} + E_o(S_{wn})^{To}}$$

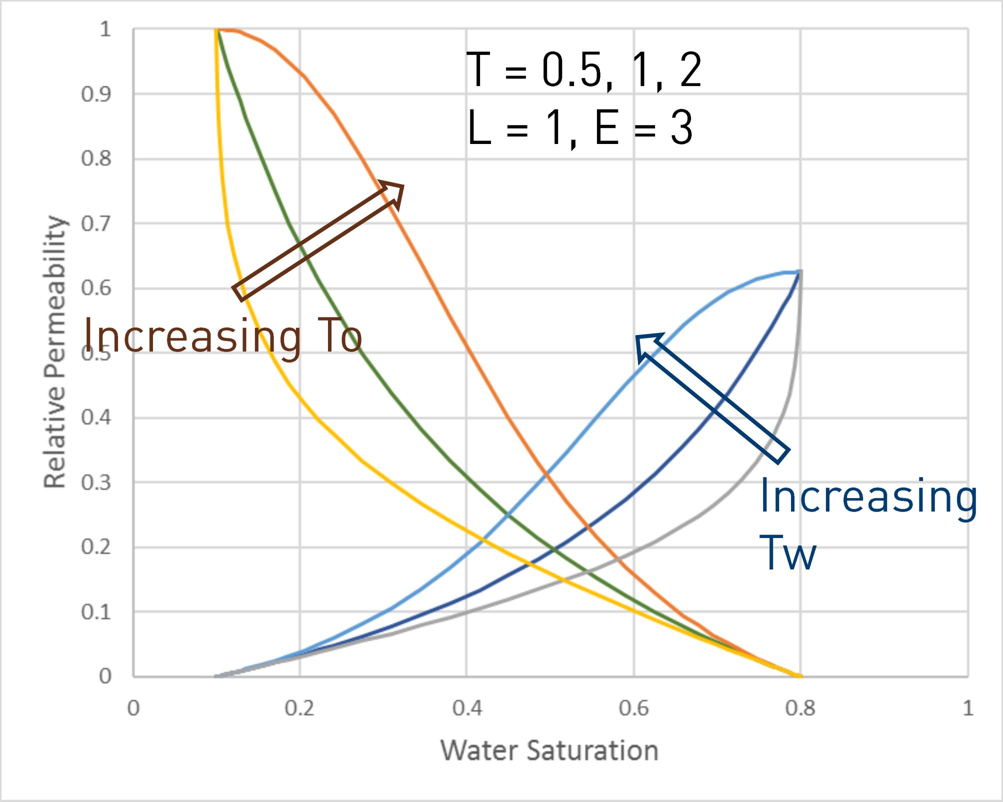


Relative Permeability Correlations

SOCIETY OF
CORE ANALYSTS

LET





Relative Permeability Correlations

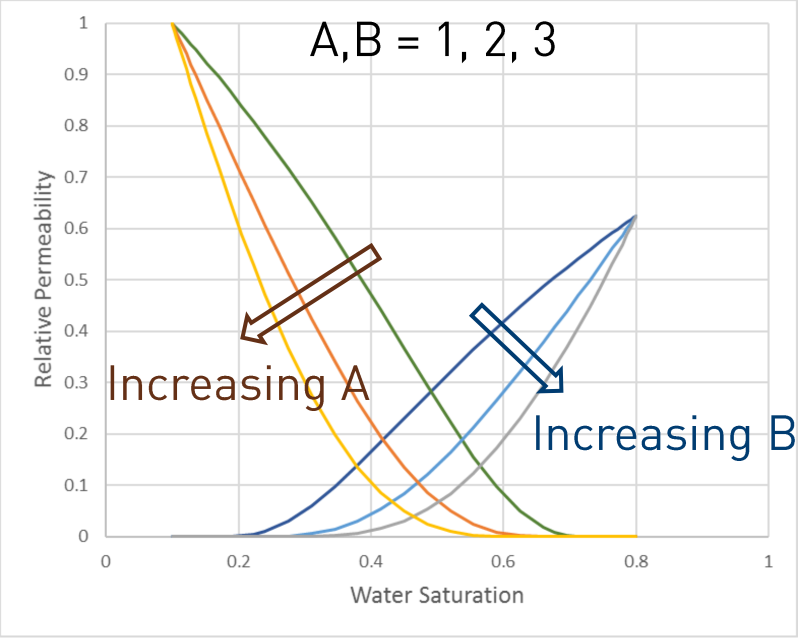
SOCIETY OF
CORE ANALYSTS

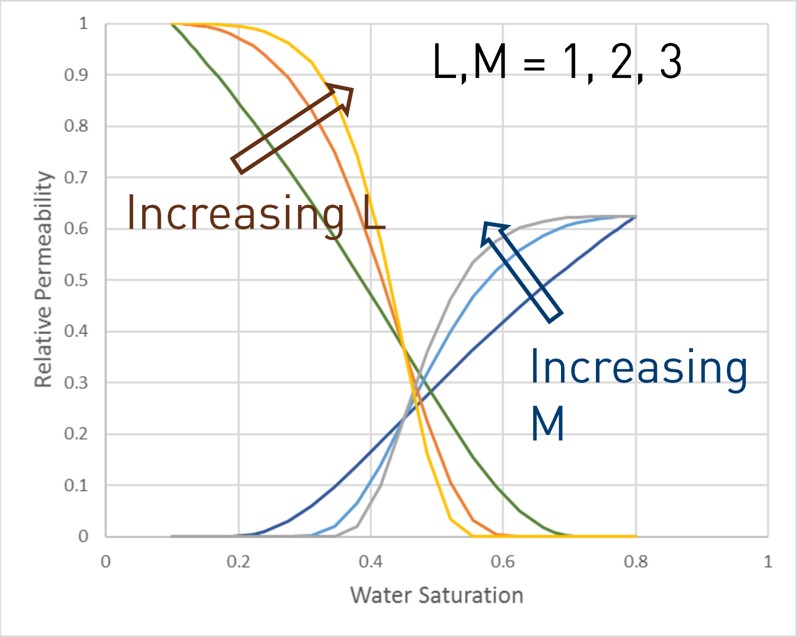
Chierici

$$k_{rw} = k_{rw}^{*}\, e^{-B\, R_w{}^{-M}}$$

$$k_{ro} = k_{ro}^{*}\, e^{-A\, R_w{}^{L}}$$

$$R_w(S_w) = \frac{S_w - S_{wi}}{1 - S_{or} - S_w}$$





Note: Rw denominator uses the changing term Sw rather than fixed Swi.

Relative Permeability Correlations

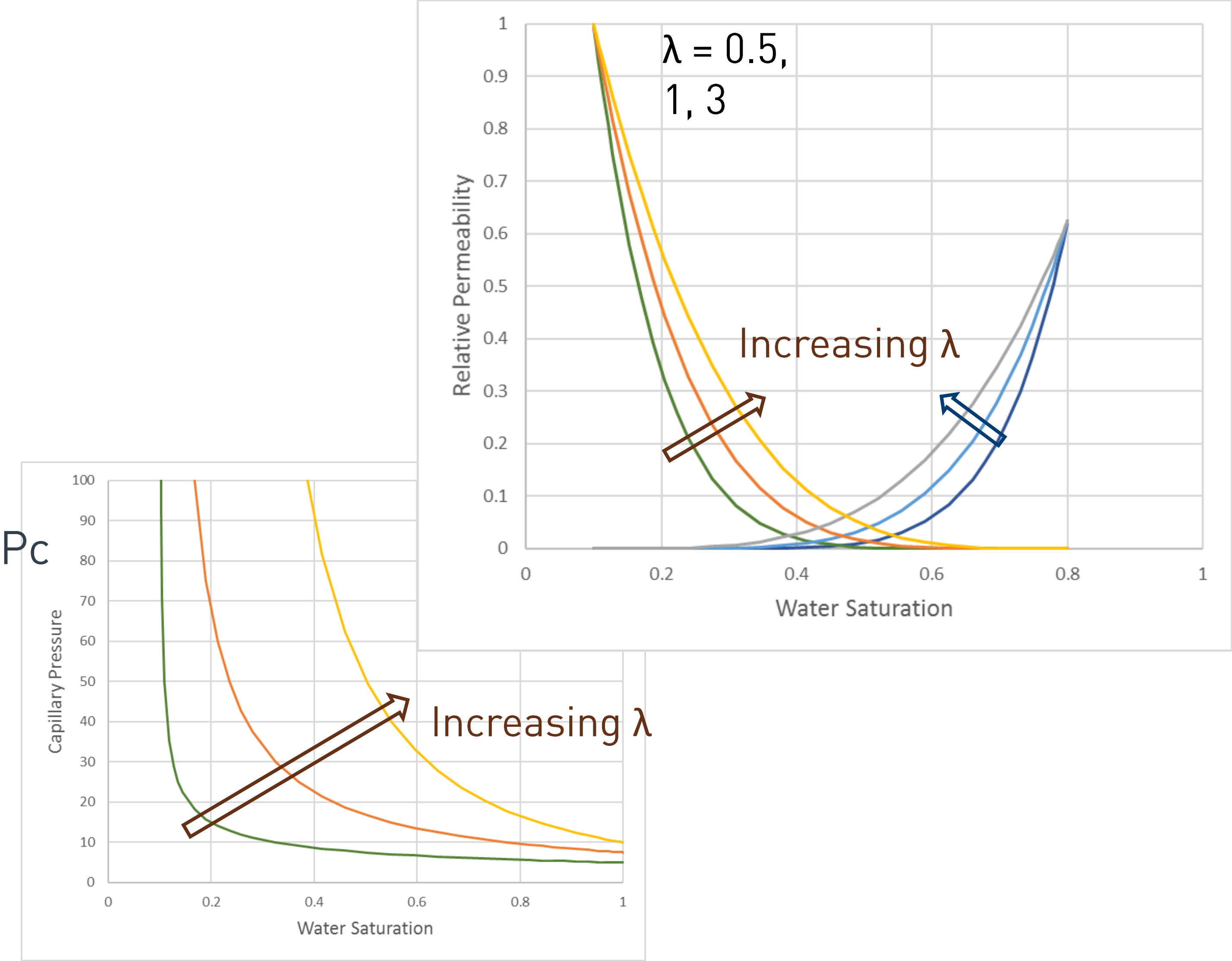
Burdine

$$k_{rw} = k_{rw}^{*}(S_{wn})^{\frac{2+3\lambda}{\lambda}}$$

$$k_{ro} = k_{ro}^{*}\,(1 - S_{wn})^{2}\,(1 - S_{wn})^{\frac{2+\lambda}{\lambda}}$$

- λ = curvature of Pc data = pore size distribution index (from Brooks-Corey Pc model)

$$P_c = P_e(S_{wn})^{-1/\lambda}$$



Relative Permeability

Simulation

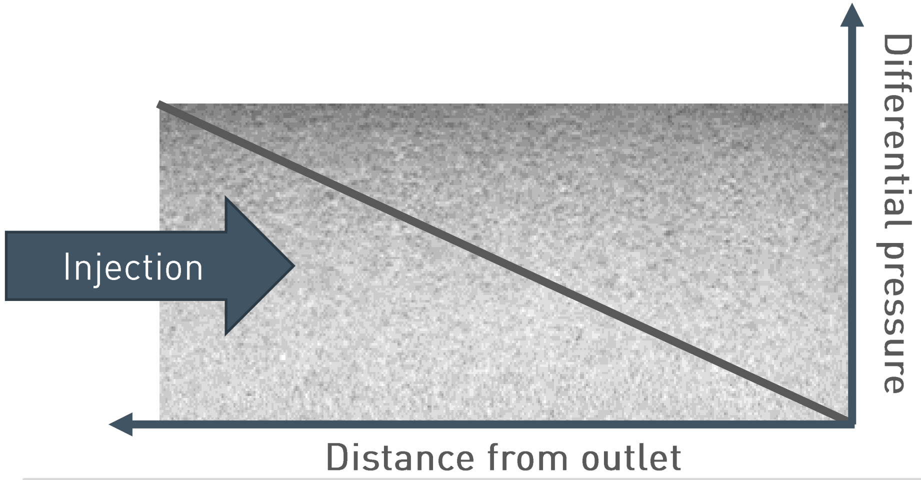
Capillary end effects

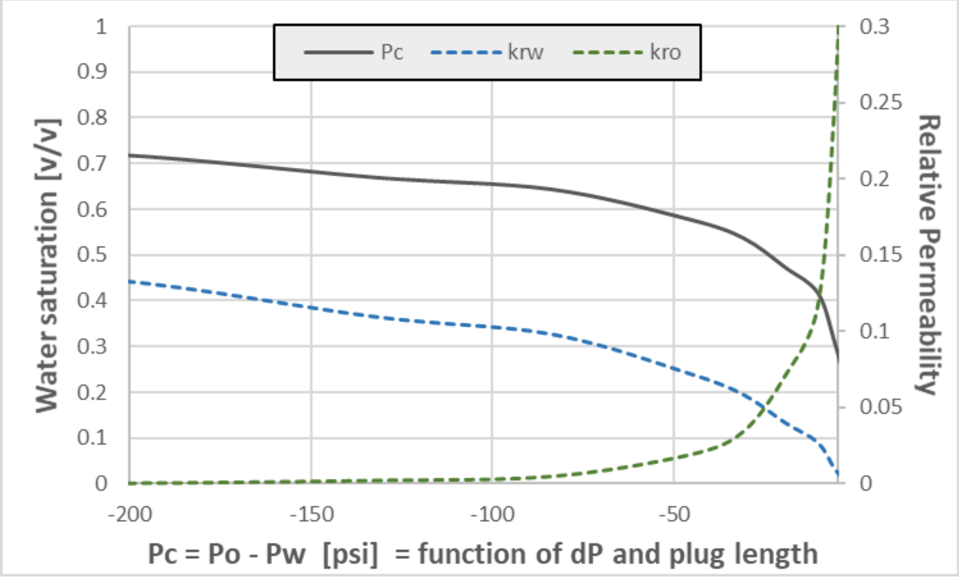
Capillary Pressure / Relative Permeability Mutual Interference

- Capillary pressure controls saturation as a function of:
  - rock properties
    - Rock composition (wetting control)
    - Pore throat size distribution (capillary distribution)
  - Fluid properties
    - Surface tension & contact angle
    - Pressure differential between the fluid phases

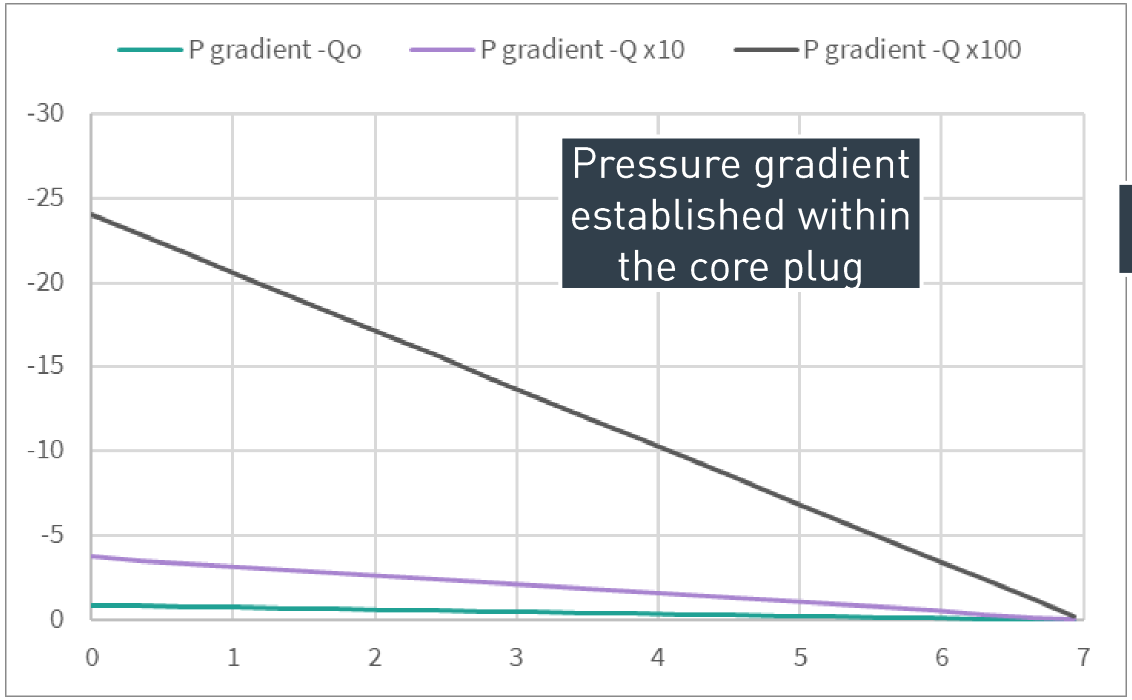
Capillary interference (simplified)

- Saturation is a function of capillary pressure (wettability), distance from Pc=0 and fluid pressure gradient
- In a coreflood, a fluid pressure gradient is applied across the plug, creating:
  - saturation gradient as a function of Pc
  - relative permeability gradient as a function of Sw
- Gradients produce error in direct calculation, since equations assume equal properties throughout

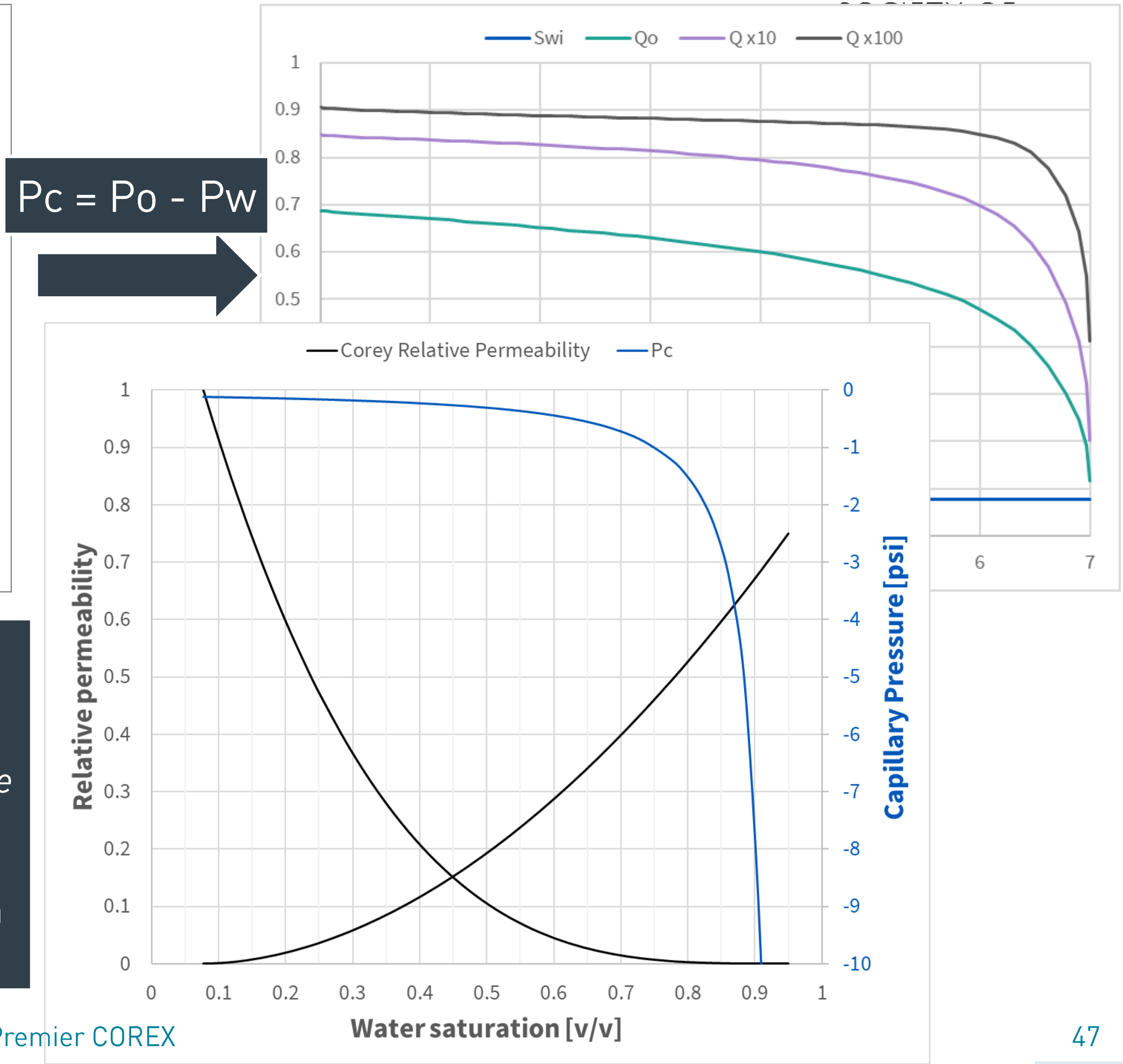




Capillary End Effects



Pressure gradient established within the core plug



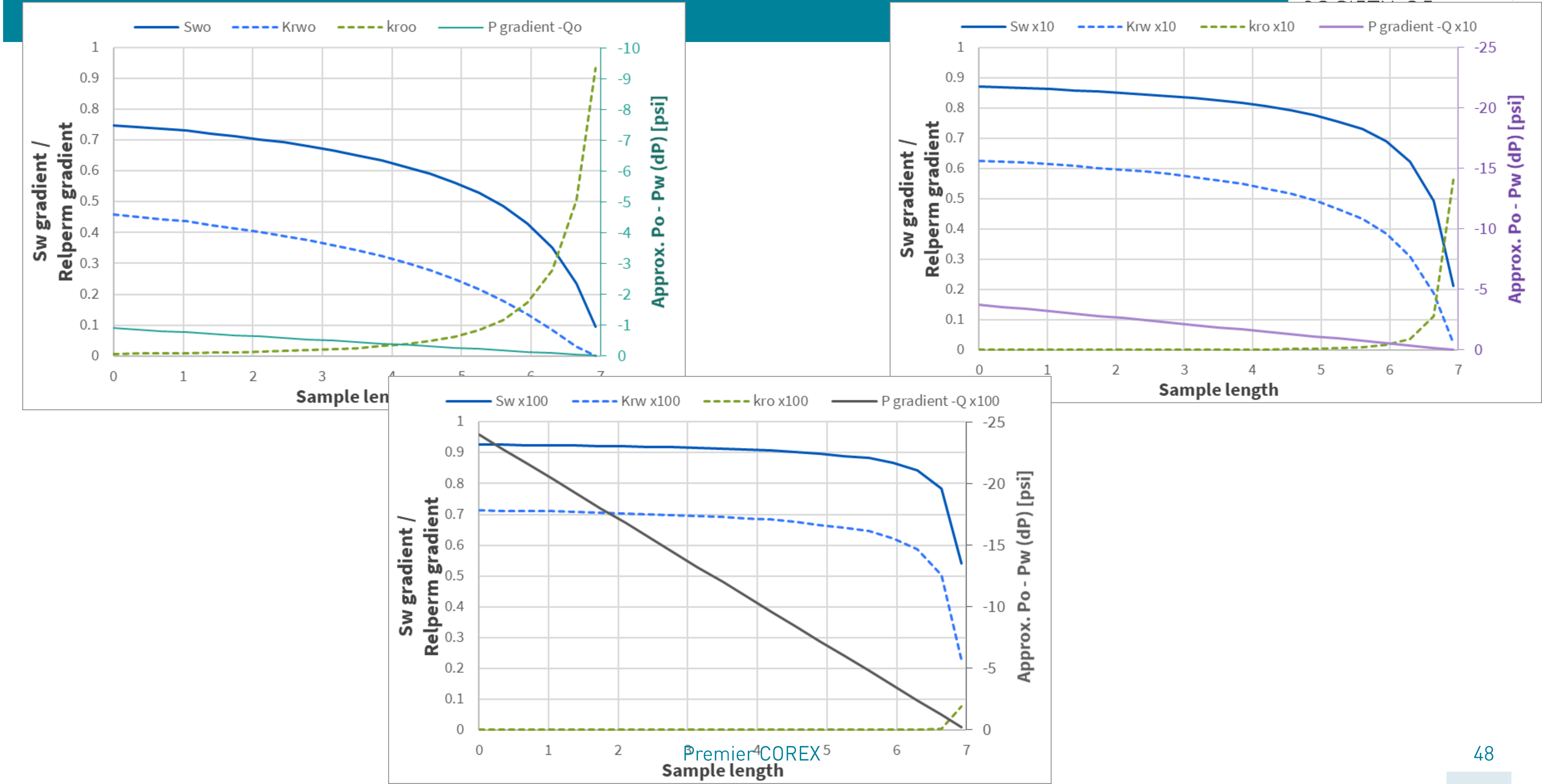
Pc = Po - Pw

Pc curve describes Sw attained under a particular pressure gradient (Pc = Po – Pw ≈ dP = f {L})

NB. - Pc = independent of relative permeability (kr) – *& vice versa*

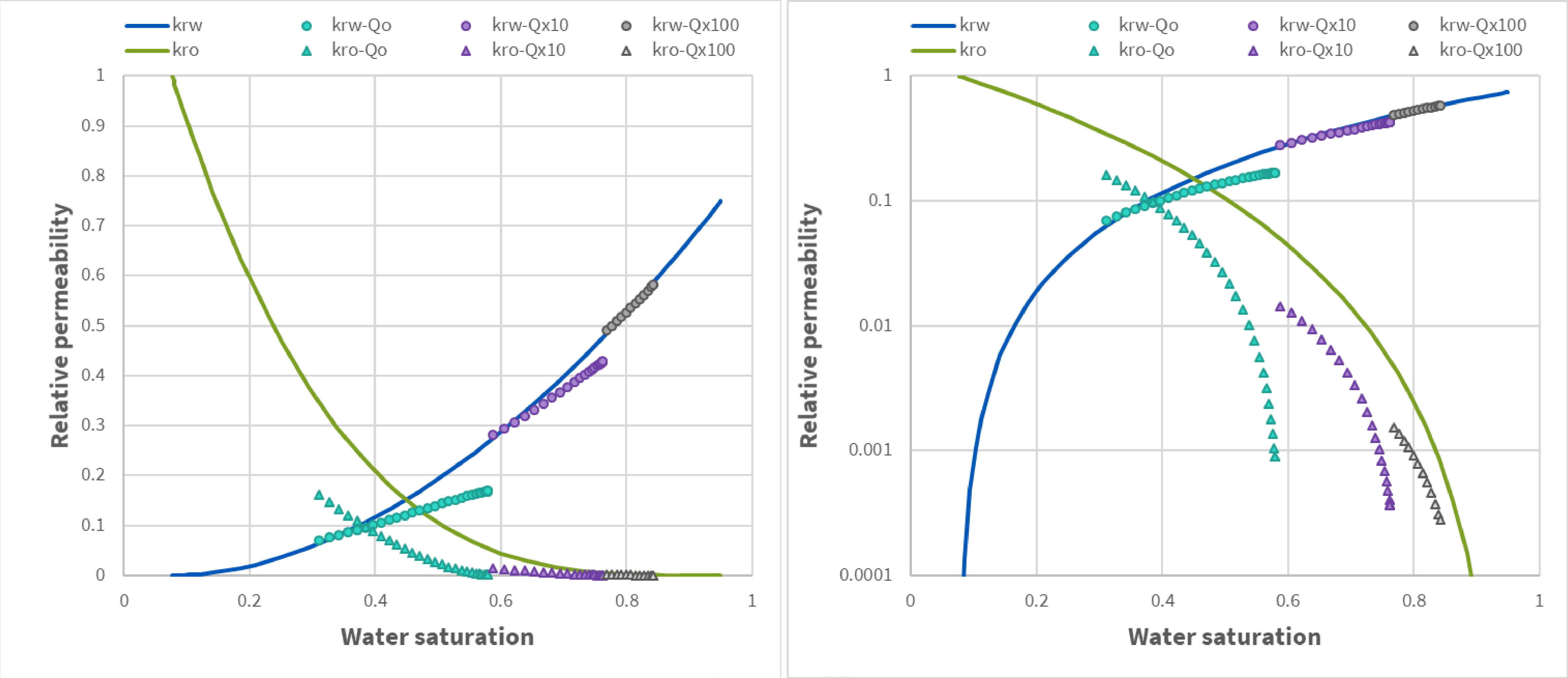
- Pc = static ¦ kr = dynamic
- kr describes how fluids are moving in the progression towards the final static (steady) state (Pc)

Capillary End Effects

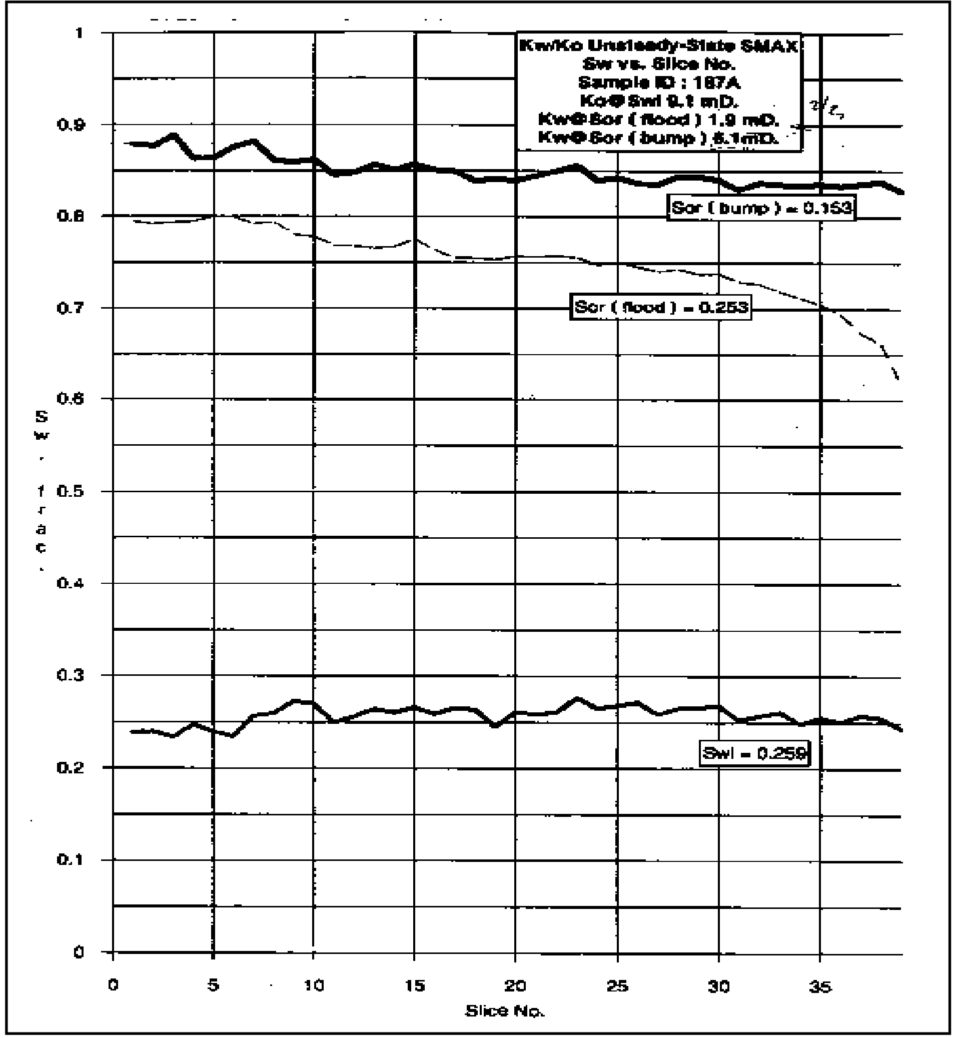


SOCIETY OF
CORE ANALYSTS

Effect on analytical relative permeability



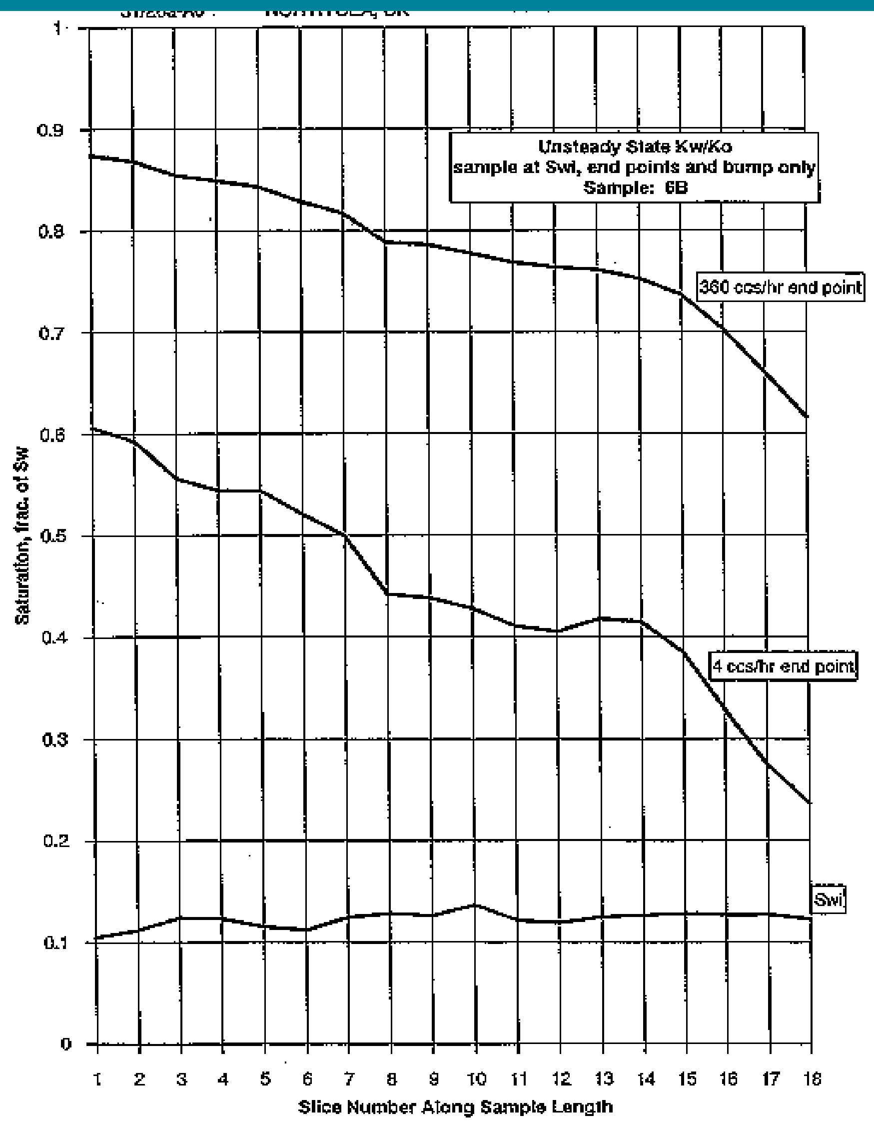
USS Flood Scans



ISSM Example 1

- uniform Swir
- end effect
- bump flood removes end effect
- some oil removed from body of plug
- neutral-slightly oil-wet ?

USS Flood Scans



ISSM Example 2

- short sample
- end effect extends through entire sample length
- significant oil produced from body of core on bump flood
- data wholly unreliable due to pre-dominant end effect.

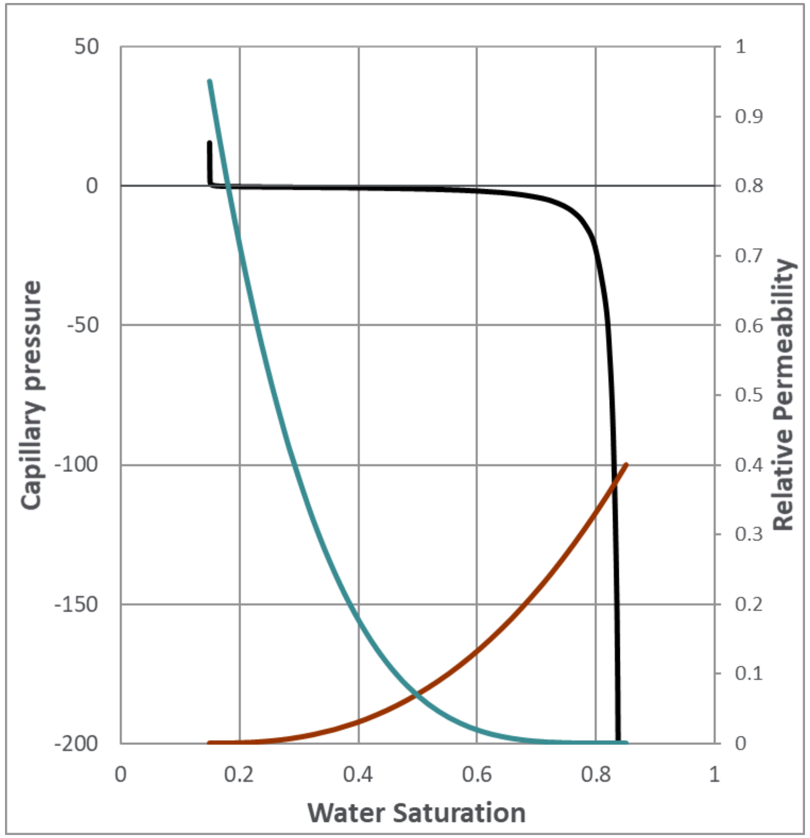
Simulation Data Input

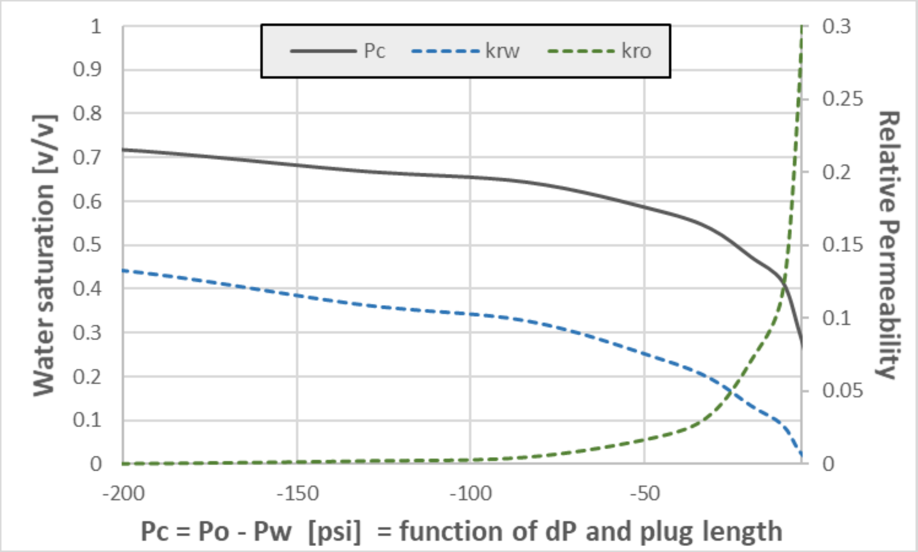
- Flood data (continuous)
  - injection rates and volumes
  - production rates
  - differential pressure
    - (check whether actual measured or static head corrected)
- Flooding orientation (horizontal, vertical)
- Fluid properties
  - viscosity, IFT, density
- Imbibition Pc curve (option)
- ISSM Scans (option)
- Beware – several non-unique solutions possible

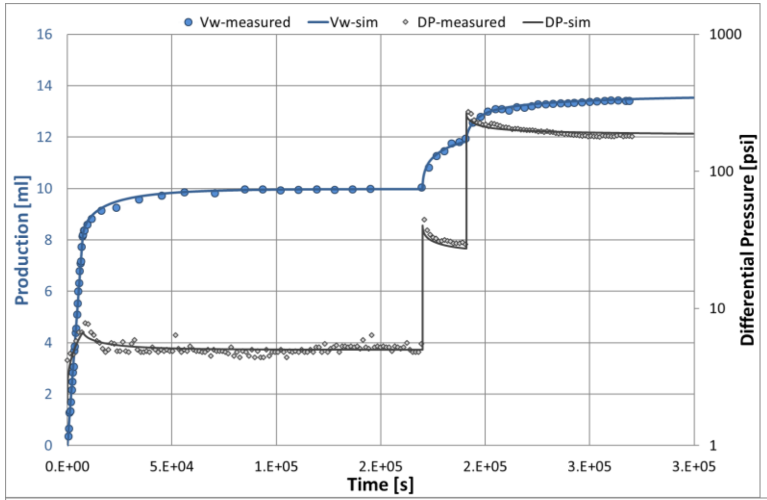
Simulation

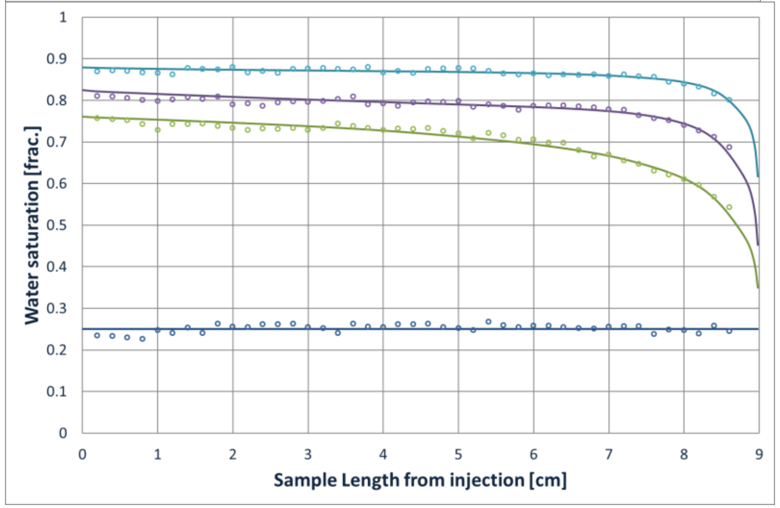
SOCIETY OF
CORE ANALYSTS

- Simulation incorporates Pc (hence, gradients) together with relative permeability to match the measured coreflood data









Coreflood Simulation

- Set up table of core properties
- Relative permeability (approx. 10^{-6} limit)
- Capillary pressure (same Saturation History)

Fluids	Water-Oil
Scenario	USS - constant rate
Imbibition/Drainage	Imbibition
Orientation	Horizontal

Sample	Sim_test	
Length	**8.00**	
Diameter	**3.80**	
Porosity	**0.220**	
Ka	**150**	
Swi	**0.250**	
Area	**11.341**	sq.cm

Fluid Properties	
Water Density	1.089 g/cc
Water Viscosity	0.432 cp
Water Compressibility	0.000 1/psi
Oil Density	0.855 g/cc
Oil Viscosity	2.697 cp
Oil Compressibility	0.000 1/psi

Relative Permeability

Data Source

Corey input

Nw	3	Swi	0.250
No	4	Sor	0
krw_max	0.510		
kro_max	0.479		

Swn	Sw	krw	Sw	kro
0.000	0.250	0.00E+00	0.250	4.79E-01
0.025	0.269	7.98E-06	0.269	4.33E-01
0.050	0.288	6.38E-05	0.288	3.90E-01
0.075	0.306	2.15E-04	0.306	3.51E-01
0.100	0.325	5.10E-04	0.325	3.14E-01
0.125	0.344	9.97E-04	0.344	2.81E-01
0.150	0.363	1.72E-03	0.363	2.50E-01
0.175	0.381	2.74E-03	0.381	2.22E-01
0.200	0.400	4.08E-03	0.400	1.96E-01
0.225	0.419	5.81E-03	0.419	1.73E-01
0.250	0.438	7.98E-03	0.438	1.52E-01
0.275	0.456	1.06E-02	0.456	1.32E-01
0.300	0.475	1.38E-02	0.475	1.15E-01
0.325	0.494	1.75E-02	0.494	9.94E-02
0.350	0.513	2.19E-02	0.513	8.55E-02
0.375	0.531	2.69E-02	0.531	7.31E-02
0.400	0.550	3.27E-02	0.550	6.21E-02
0.425	0.569	3.92E-02	0.569	5.24E-02

Capillary Pressure

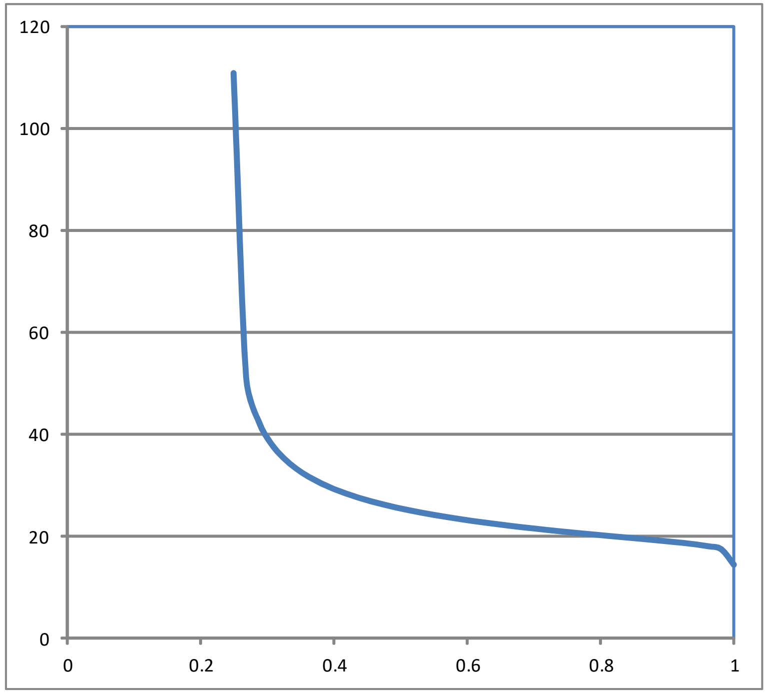
Data Source

Tabular data

Units	**Pa**
Cw	20
Aw	0.26
Co	1
Ao	0.25

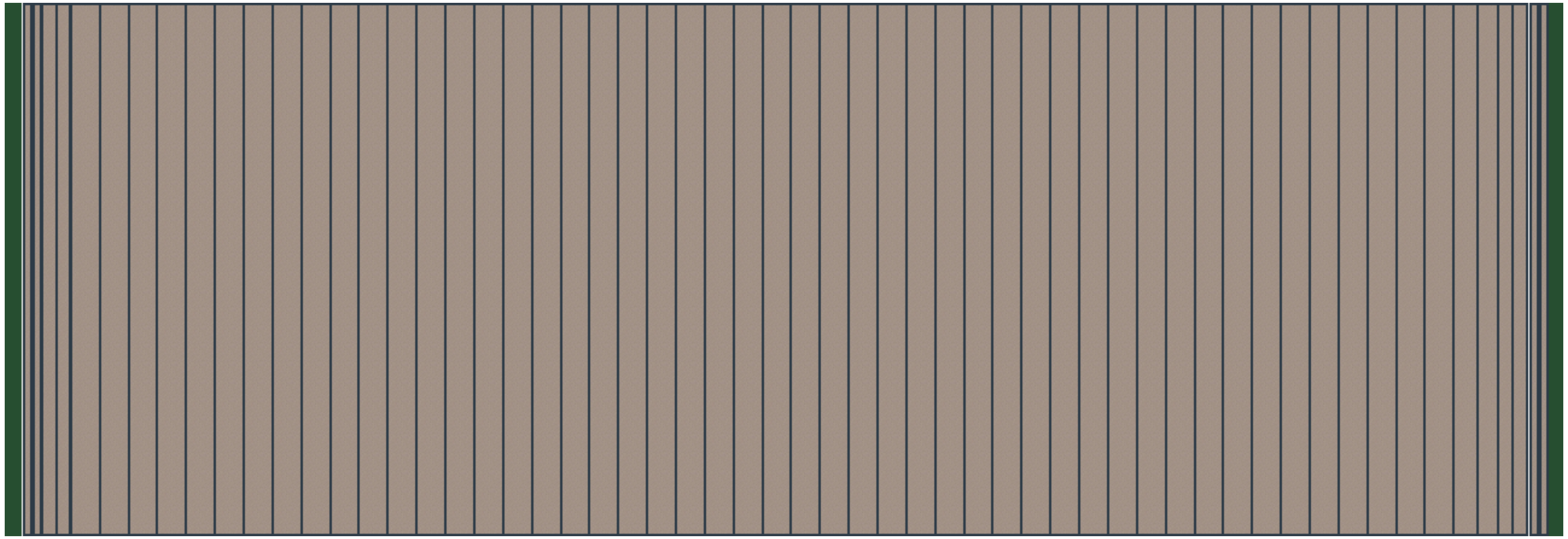
Sw	Pc ow
0.250	1.11E+02
0.269	5.11E+01
0.288	4.25E+01
0.306	3.81E+01
0.325	3.53E+01
0.344	3.32E+01
0.363	3.16E+01
0.381	3.03E+01
0.400	2.93E+01
0.419	2.83E+01
0.438	2.75E+01
0.456	2.68E+01
0.475	2.62E+01
0.494	2.56E+01
0.513	2.51E+01
0.531	2.46E+01
0.550	2.42E+01
0.569	2.37E+01

$$P_c = \frac{c_w}{\left(\frac{S_w - S_{wi}}{1 - S_{wi}}\right)^{a_w}} - \frac{c_o}{\left(\frac{1 - S_w - S_{or}}{1 - S_{or}}\right)^{a_o}}.$$



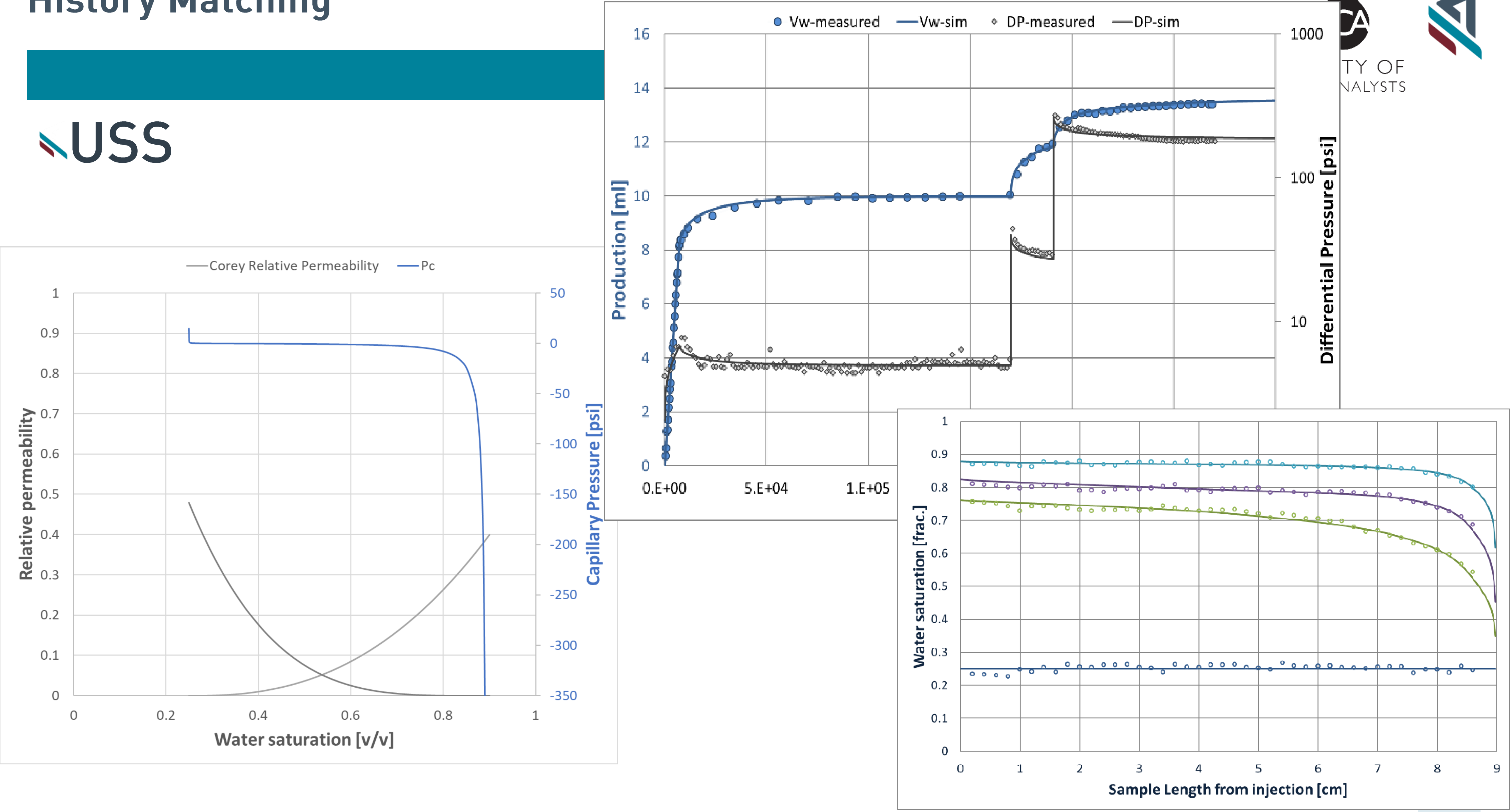
Coreflood Simulation

- 30 – 200 grid blocks
- Some refine towards inlet/outlet



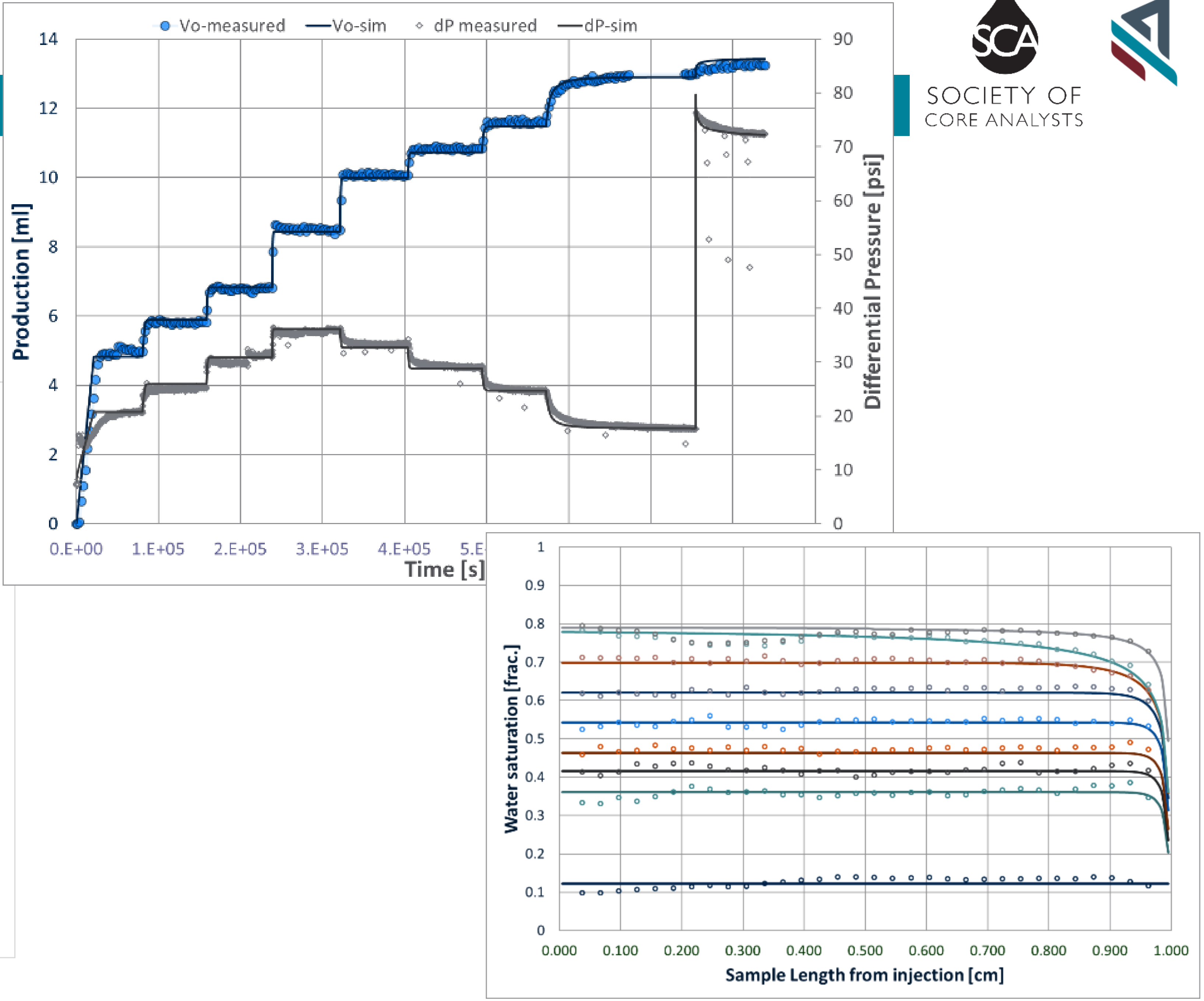
History Matching

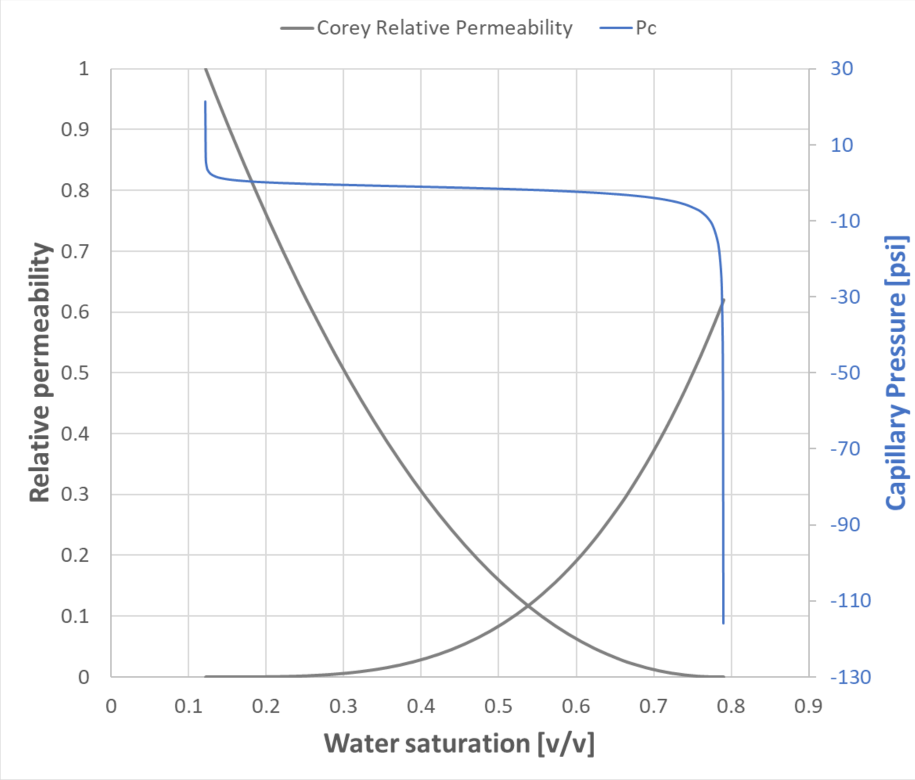
USS



History Matching

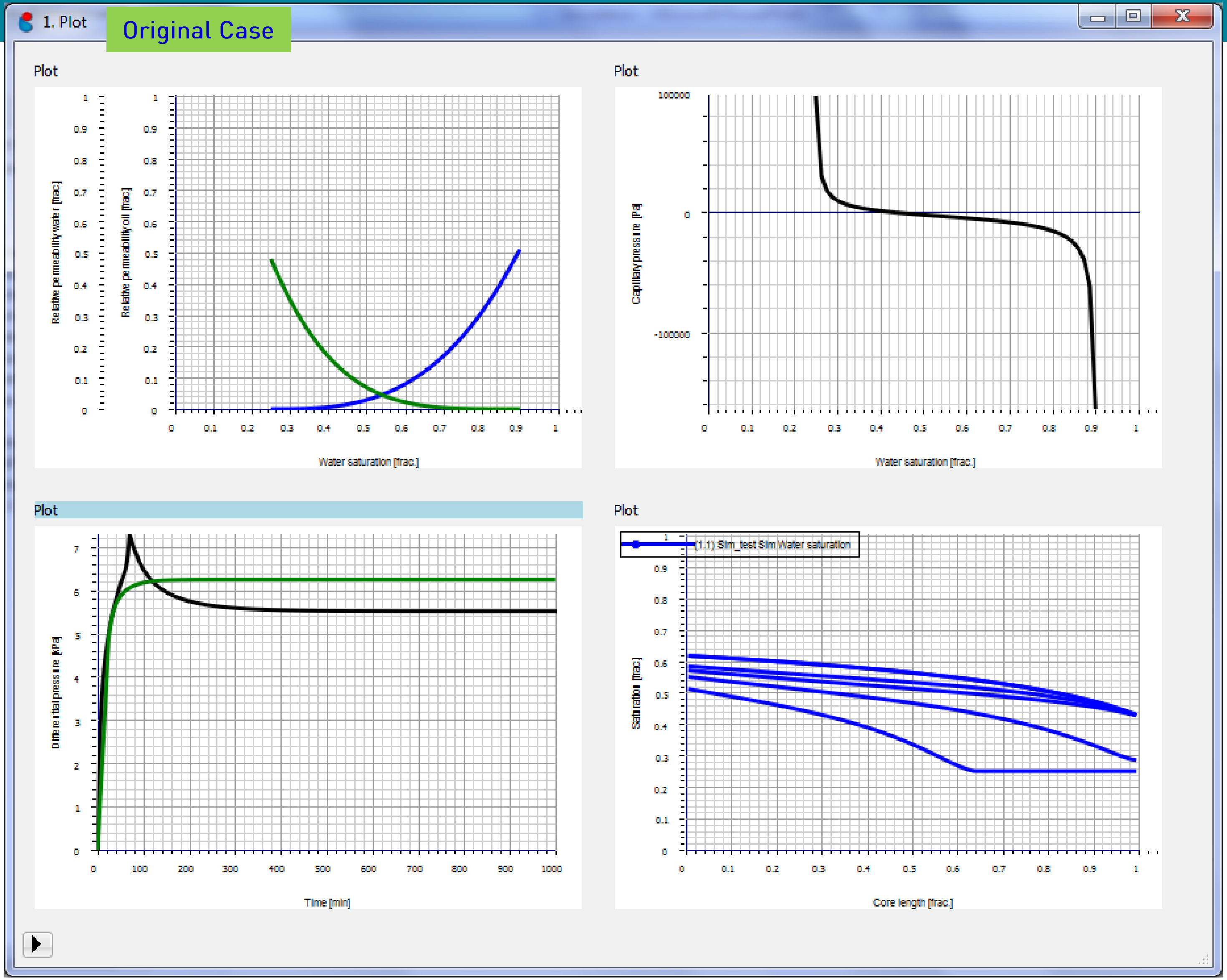
SS





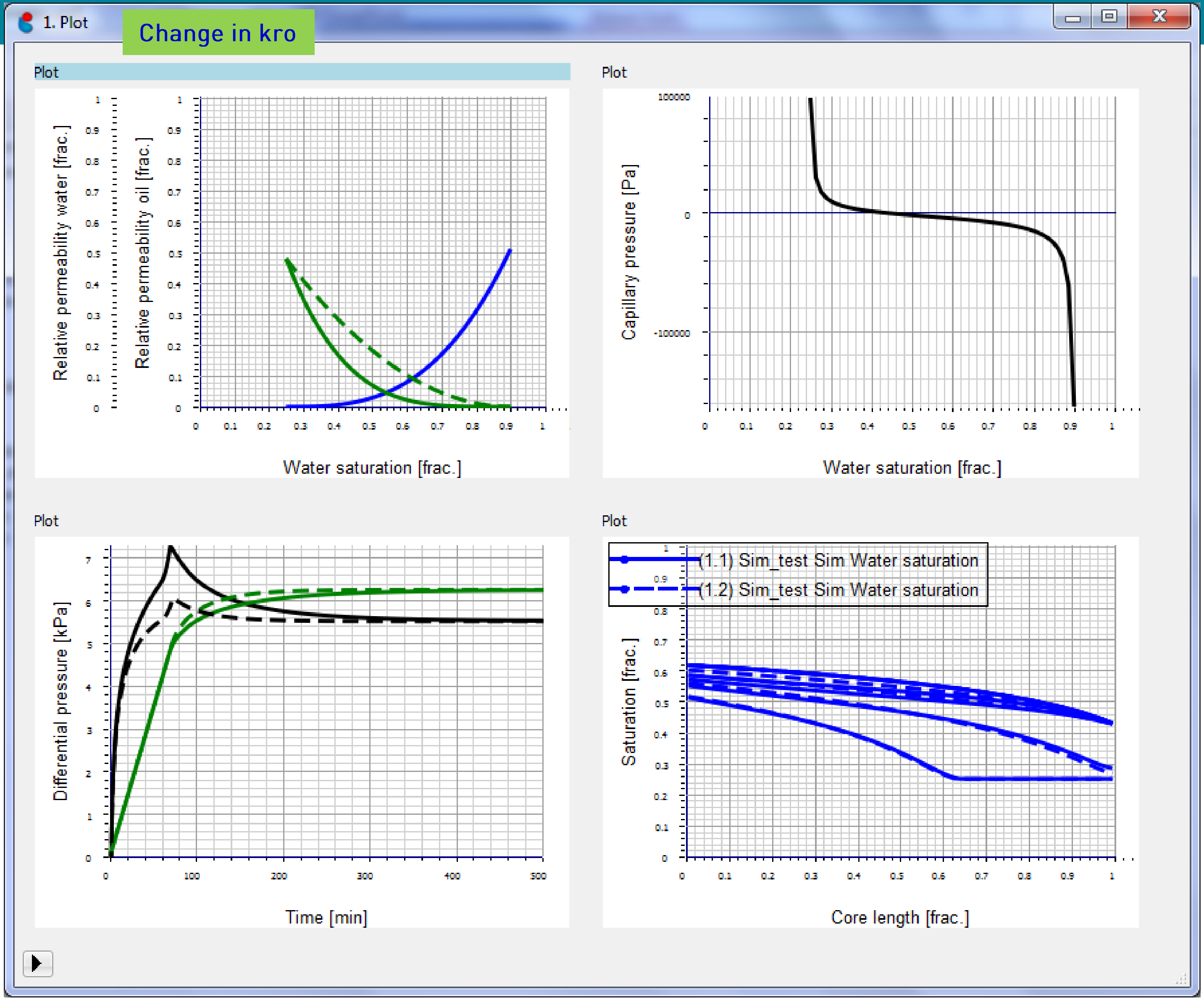
Coreflood Simulation

SOCIETY OF CORE ANALYSTS


Original Case

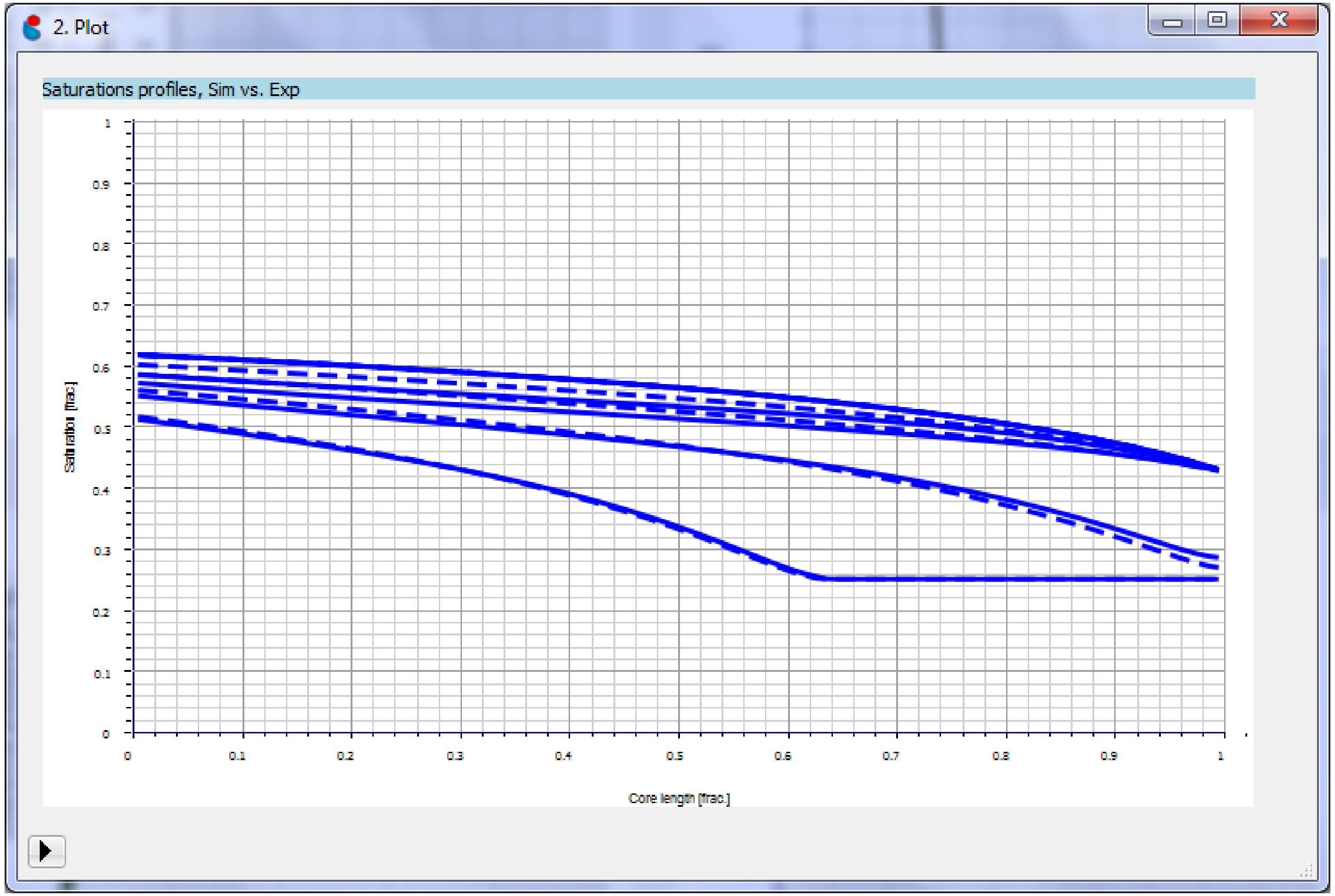
Coreflood Simulation

SOCIETY OF
CORE ANALYSTS



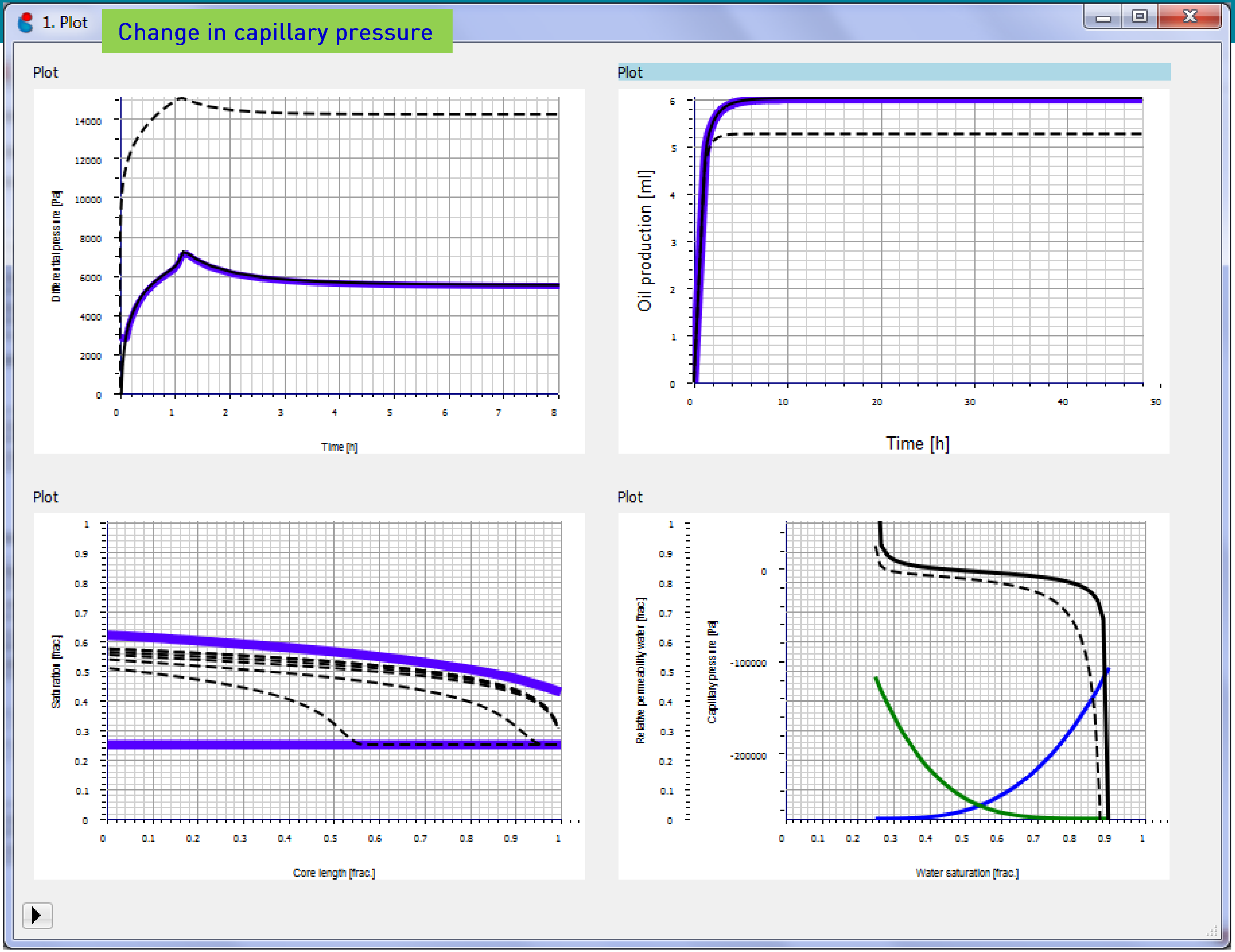
Coreflood Simulation

SOCIETY OF
CORE ANALYSTS



Coreflood Simulation

SOCIETY OF
CORE ANALYSTS



Change in capillary pressure

Conclusions

- Perform at representative wettability
- Perform with representative samples & fluids
- QC data
- Derive correlations to reservoir properties
  - If sufficient data available
- Use coreflood simulation to derive relative permeability curves

SOCIETY OF CORE ANALYSTS

Thank You!
Questions?

PREMIER COREX

www.pofg.com/corex

Contact details:
Jules Reed
Global Technical Manager
jules.reed@pofg.com
www.pofg.com/corex