WAG hysteresis

Fluid Flow Mechanisms for Miscible and Immiscible WAG

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SPE 169747

Status of Fluid Flow Mechanisms for Miscible and Immiscible WAG

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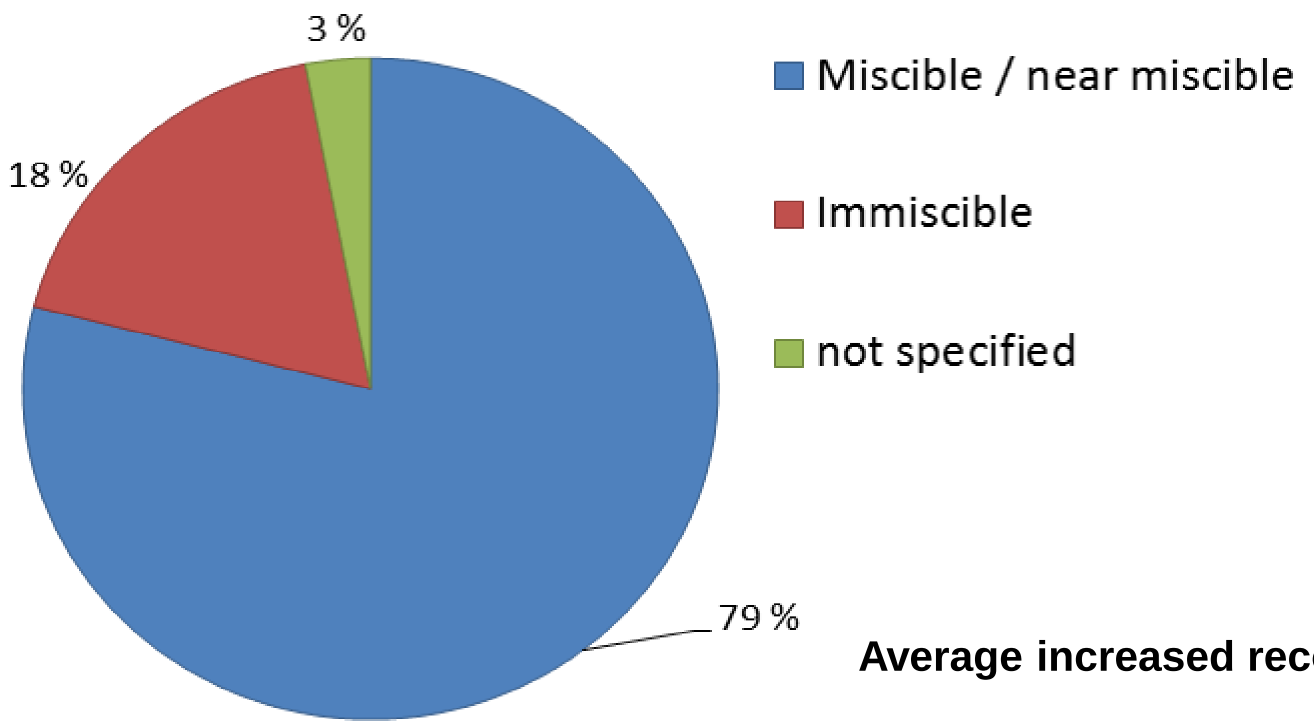
Miscible and Immiscible WAG



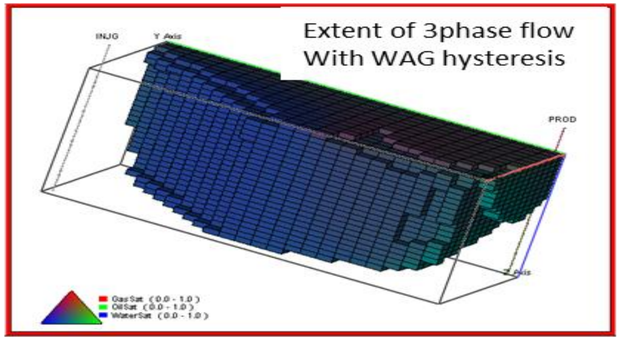
Average increased recovery : 5-10 % OOIP

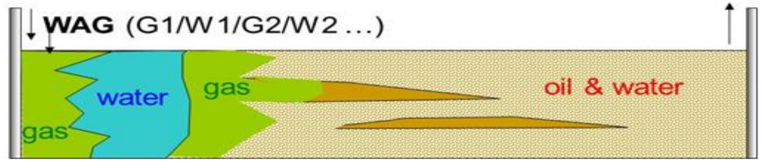
Miscible applications : 9.7 %
Immiscible applications : 6.4 %

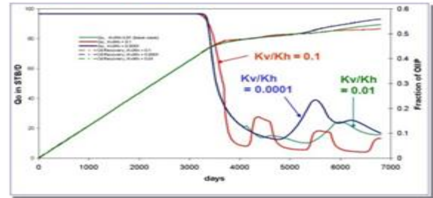
Source: Christensen, J.R., Stenby, E.H. and Skauge, A.: "Review of WAG Field Experience," SPE 71203, *SPERE &E Journal*, 97-106, April 2001

Miscible and Immiscible WAG

FIELD SCALE



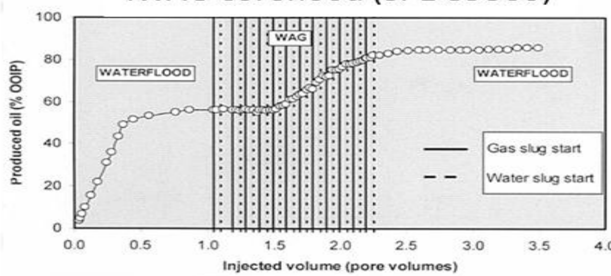




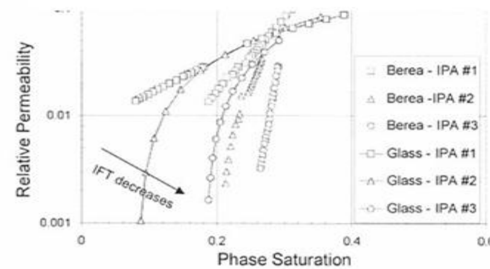
WAG cycling – oil recovery

CORE SCALE

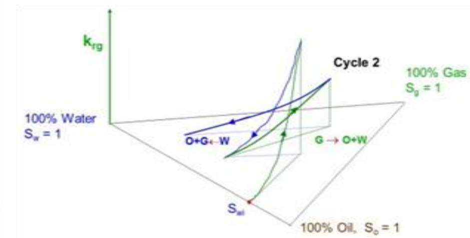
IWAG coreflood (SPE 89360)



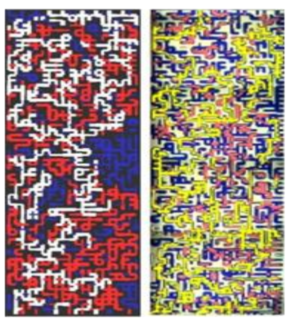
Rel perms vs. IFT (SPE 90572)



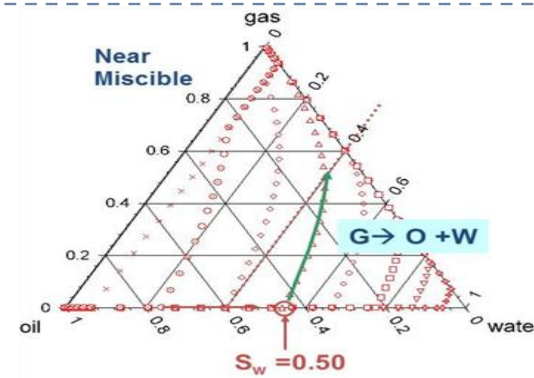
Rel perm hysteresis in WAG



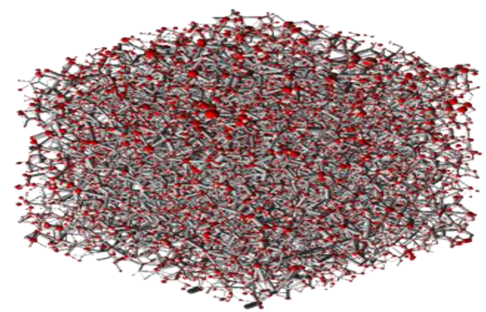
PORE SCALE



3 phase WAG displacements

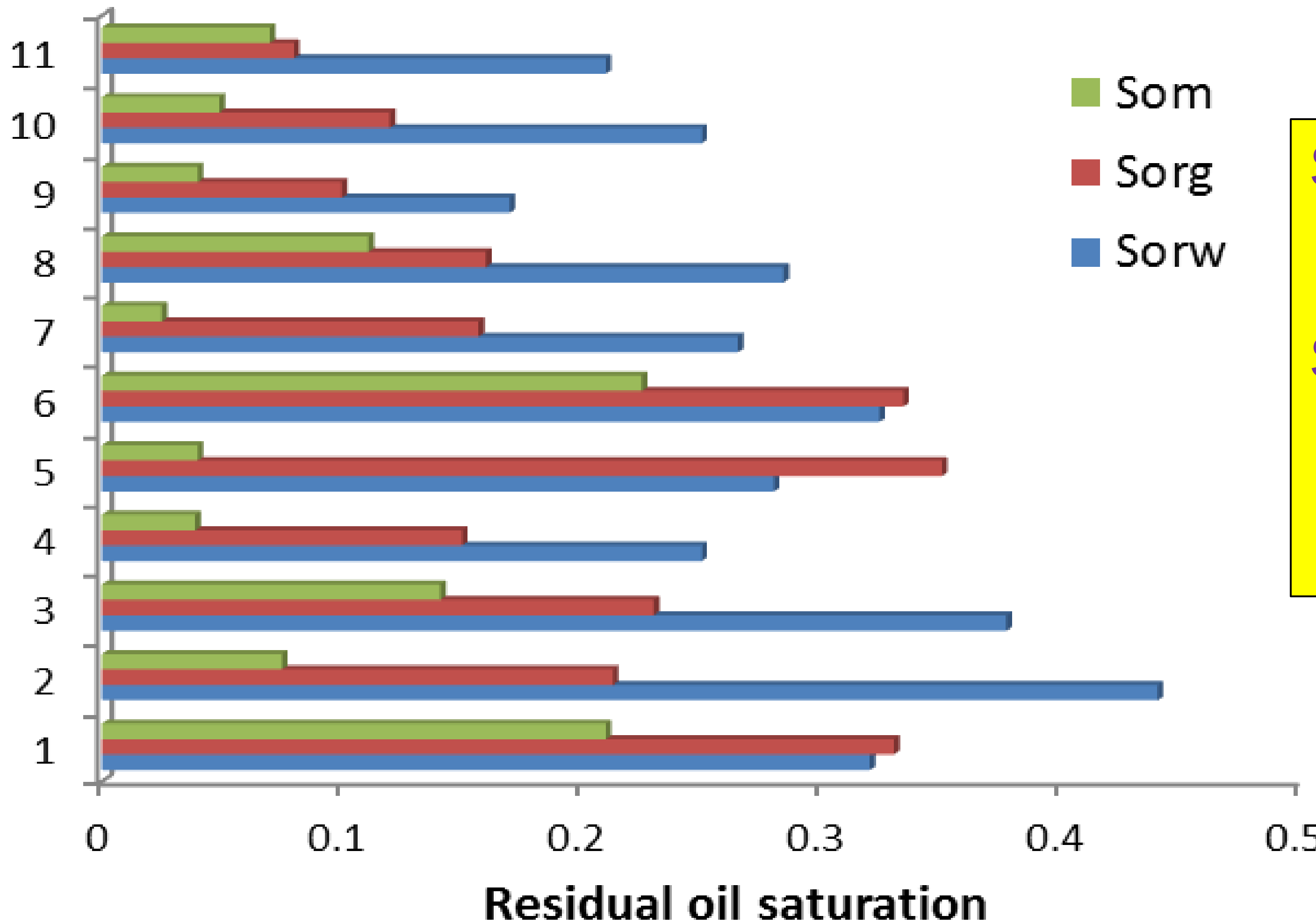


Phase paths



3D network model

Immiscible WAG



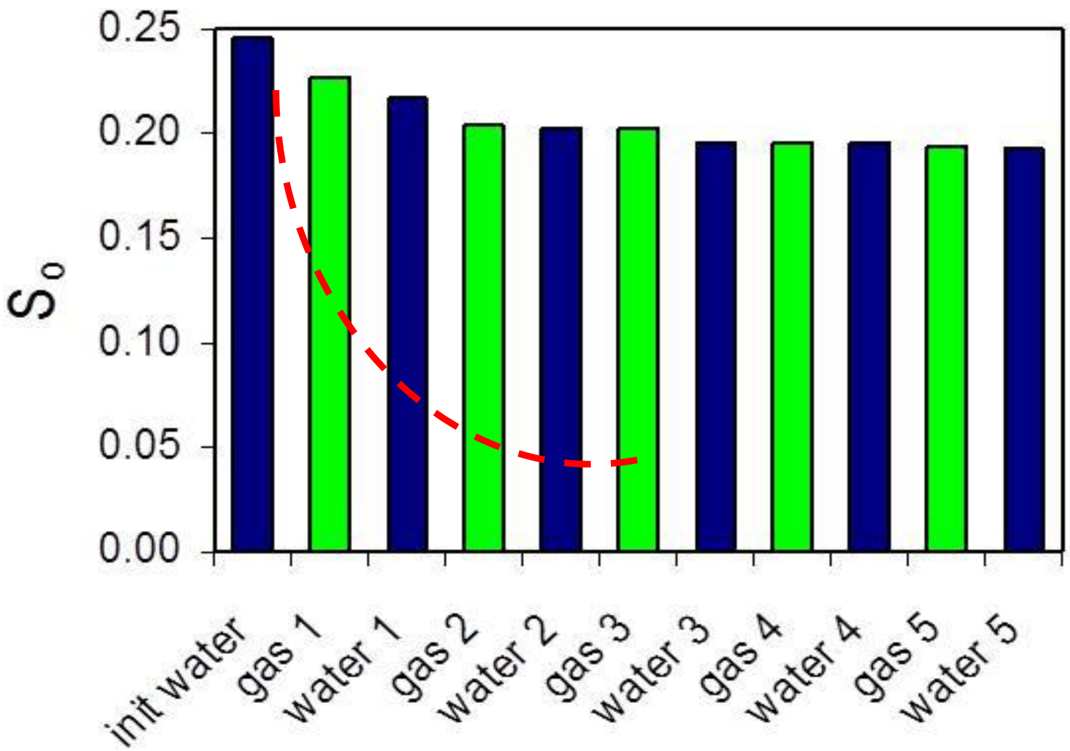
$S_{orw} > S_{om}$ (3ph)

$S_{orw} = S_{om} + K \cdot S_{gt}$

$0 < K < 1$

Immiscible WAG

Experimental micromodel study of oil recovery by WAG displacement



$1/S_{gt}$ - $1/S_{gi}$ = C

$S_{orw} = S_{om} + K \cdot S_{gt}$

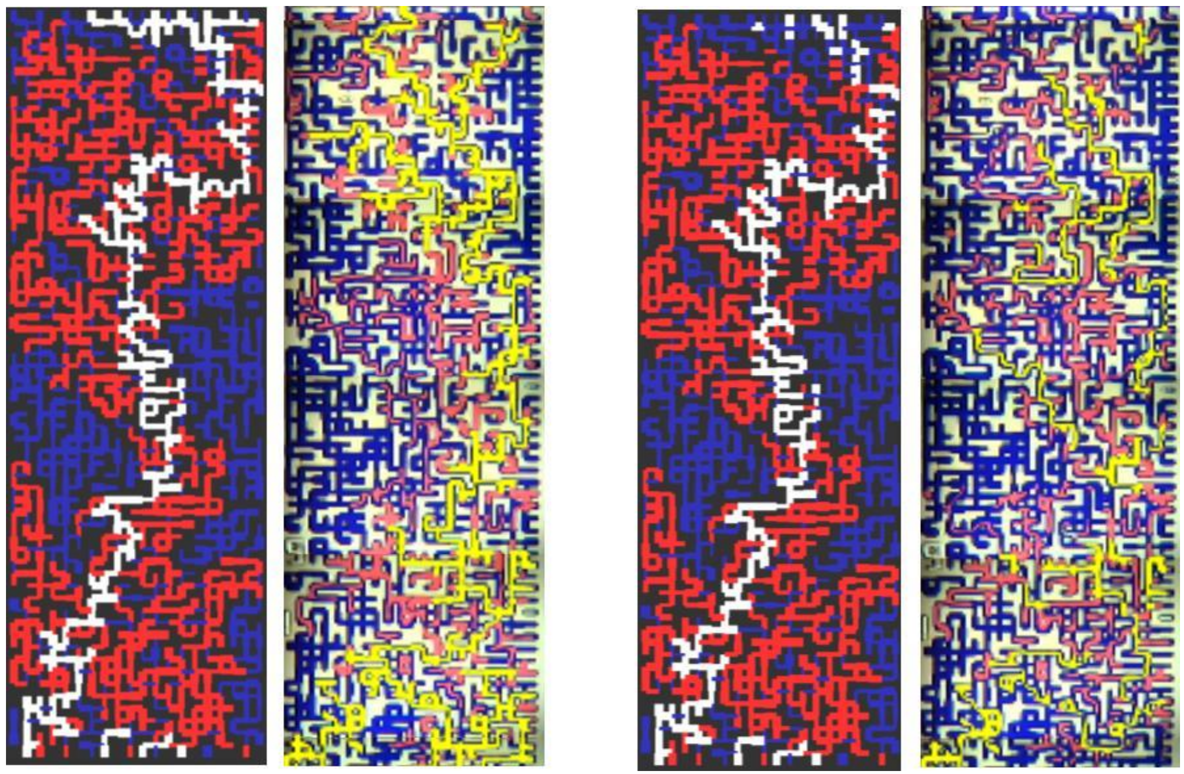
van Dijke et al (2010)

Dashed line is from core experiments using 0.1 PV slugs

Same phenomena, but higher gas trapping with small slugs, higher aspect ratio, and smaller pores (higher Pc) in cores

Immiscible WAG

Comparison of fluid distributions from 3 phase WAG network model

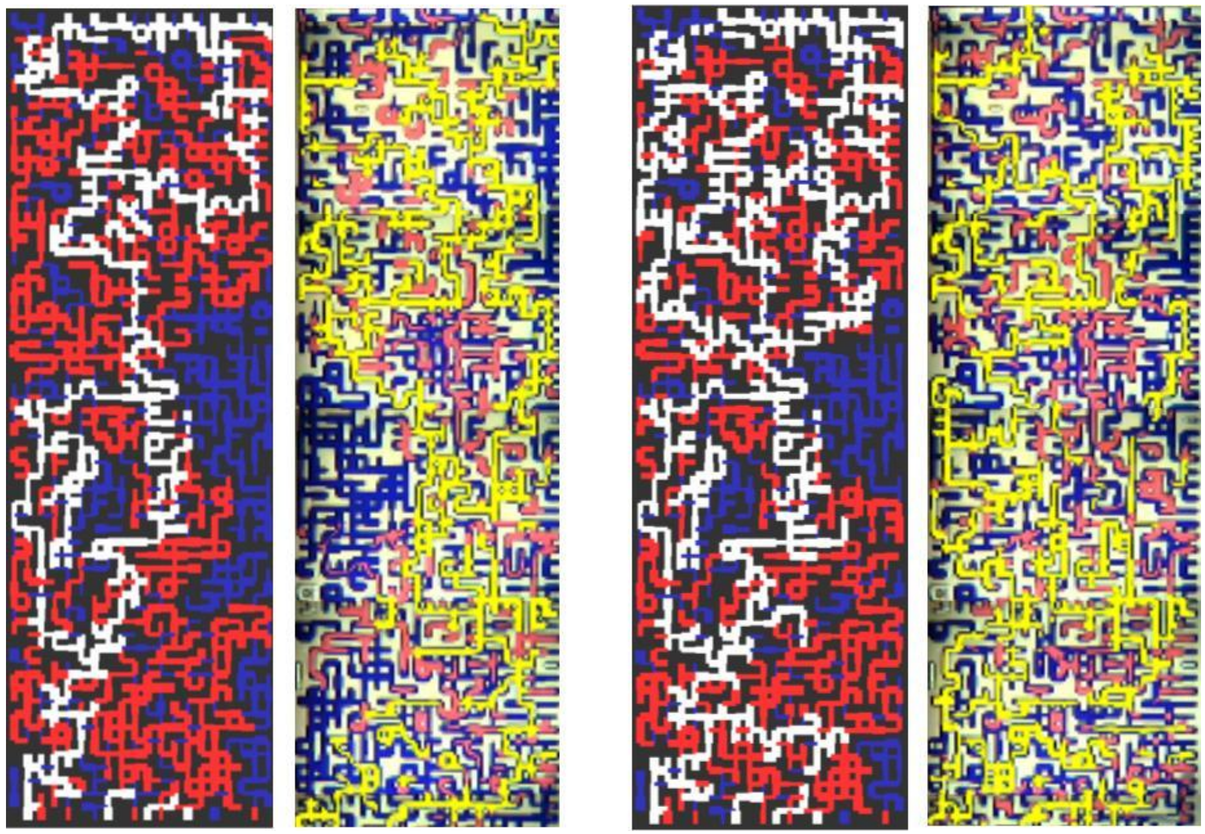


(a) First gas flood G1 from Swi (b) First waterflood W1 after gas G1

Gas injection into least resistance path (biggest pores filled with oil)

Immiscible WAG

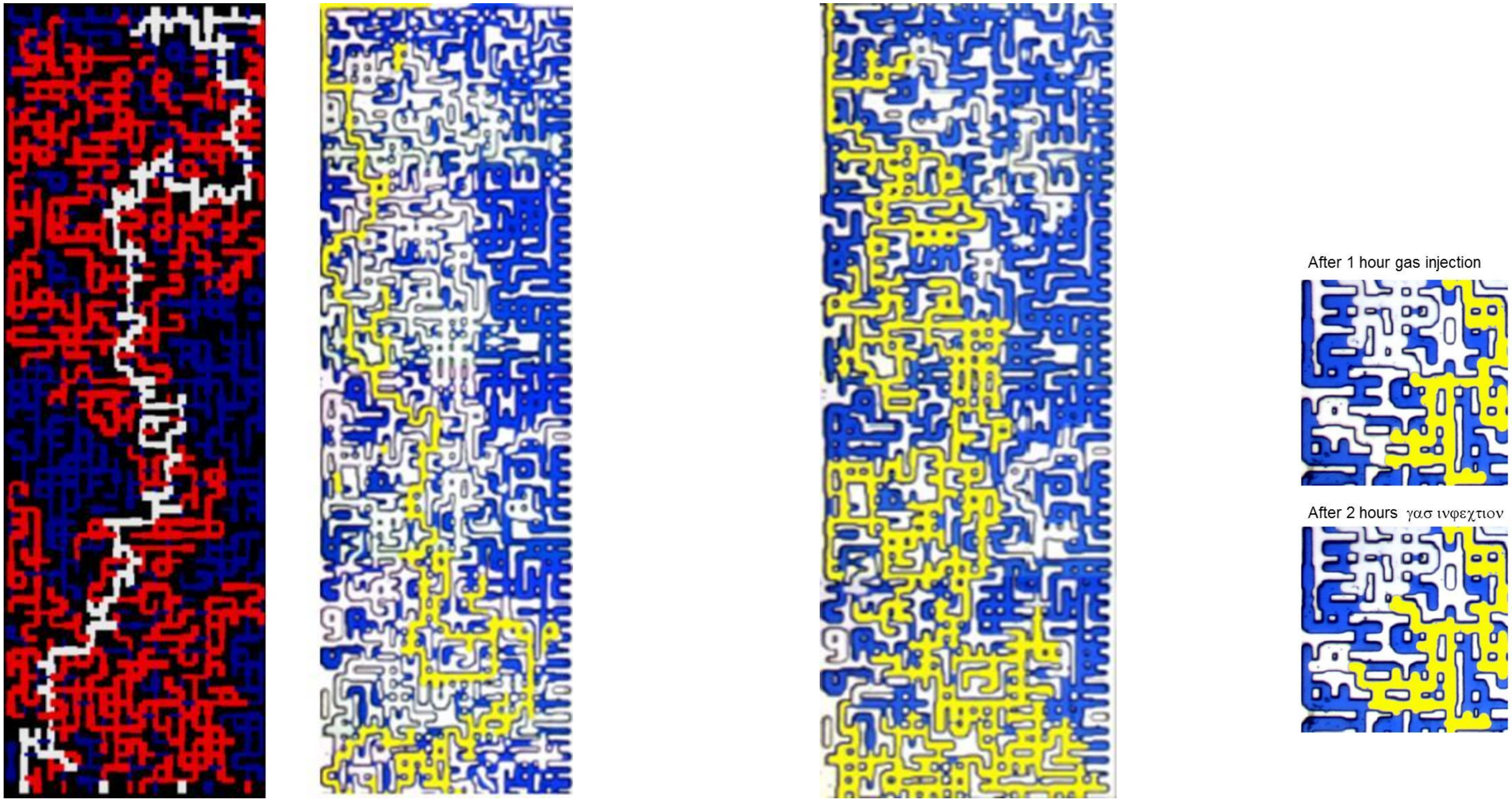
Comparison of fluid distributions from 3 phase IWAG network model



(a) 2nd gas injection (G2) after W1 (b) After 5th Gas injection (G5)
Gas finds new path and thereby improves microscopic sweep

Miscible and Immiscible WAG

Comparison of fluid distributions from 3 phase nMWAG network model

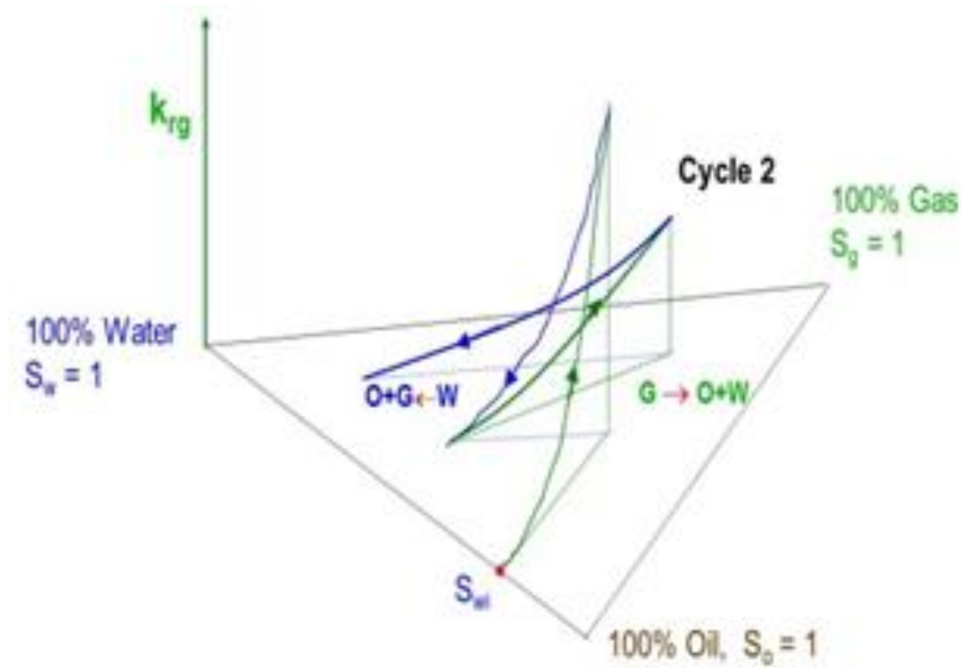


(a) gas injection G2 (b) initial G2 in nMWAG (c) G2 after longer gas injection (d) local expansion of gas finger

Swelling of gas fingers and local expansion (nM) while ImM gives new and disconnected gas paths

Miscible and Immiscible WAG

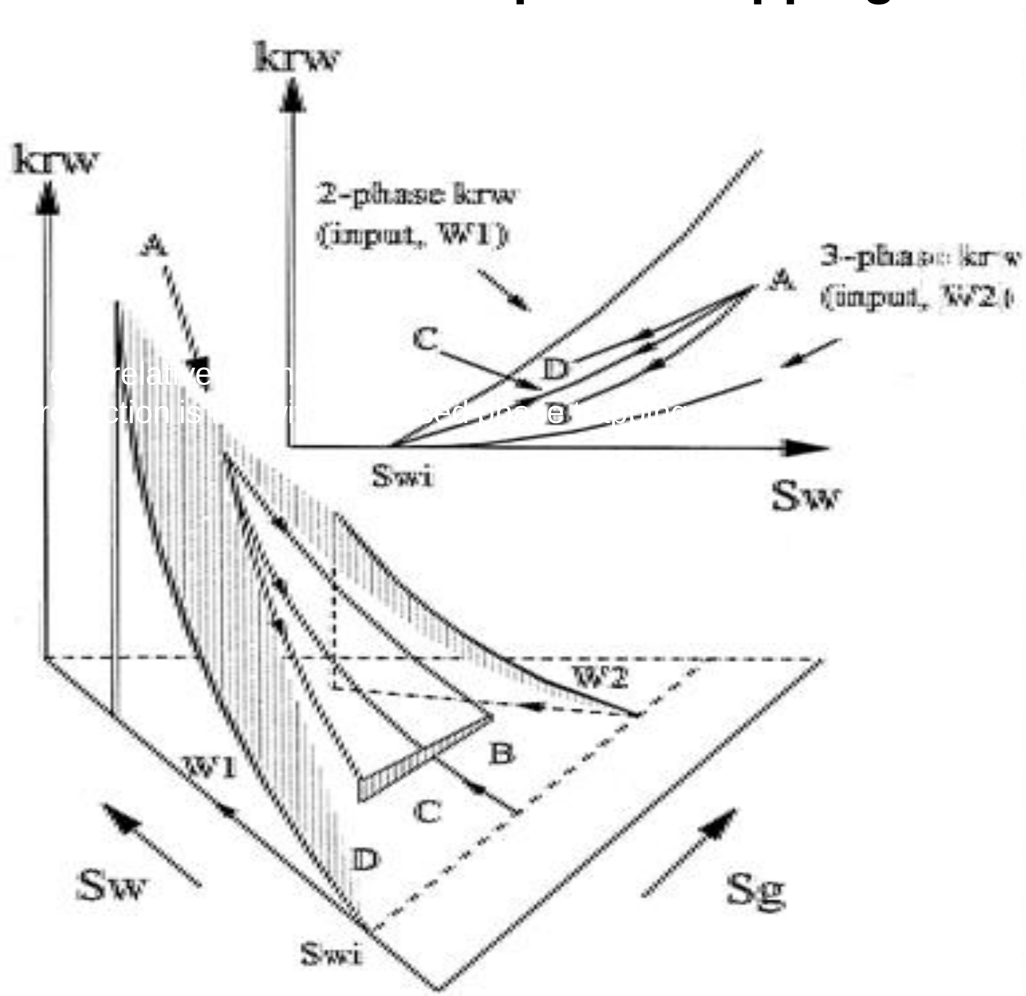
Three-phase gas relative permeability
Subsequent reduction is krg with increased phase trapping.



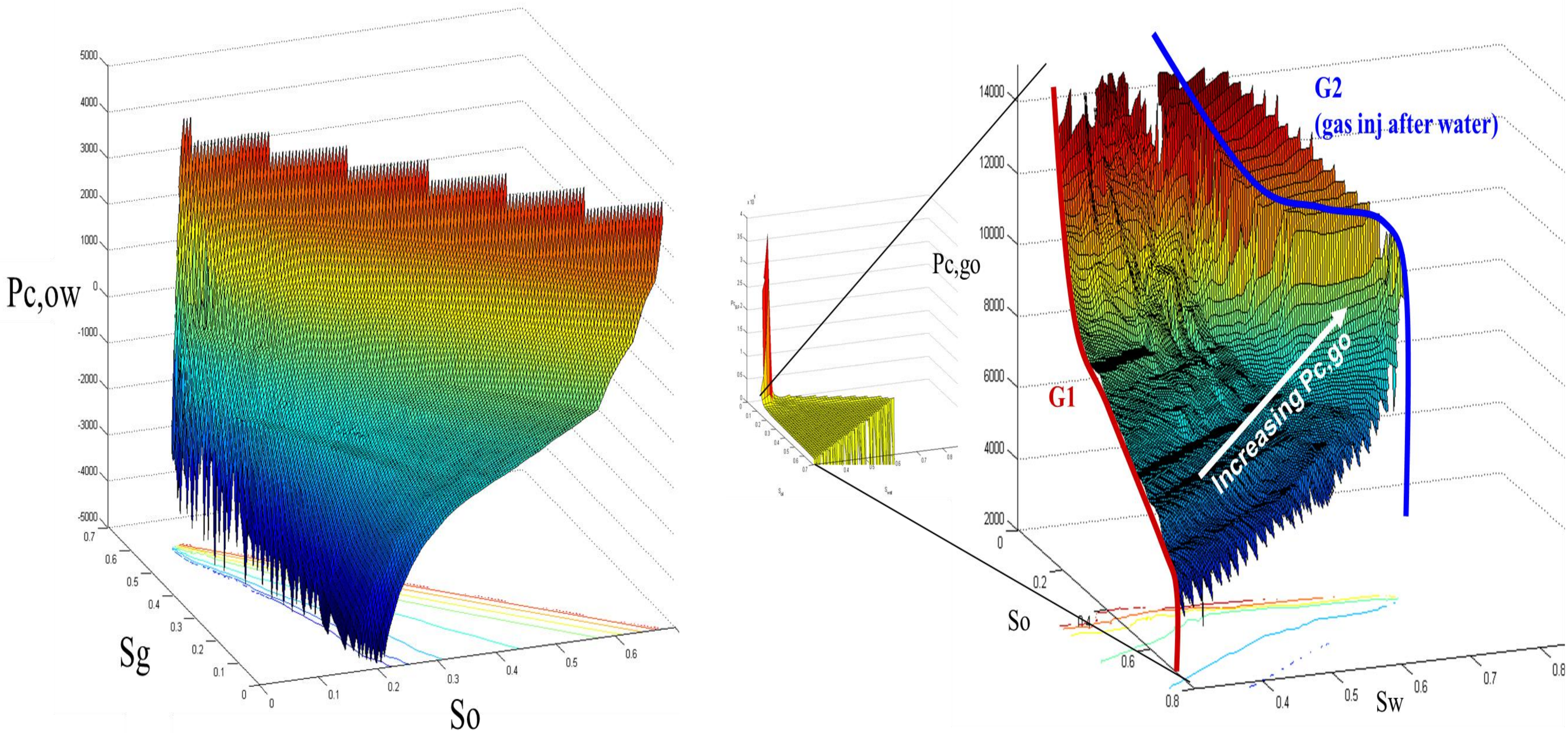
Larsen, J.A., and Skauge, A.: "Methodology for Numerical Simulation with Cycle-dependent Relative Permeabilities," *Soc. Petr. Enginering Journal*, 163- 73, June 1998.

Miscible and Immiscible WAG

Three-phase water relative permeability
Subsequent reduction is krw with increased phase trapping.



Immiscible WAG



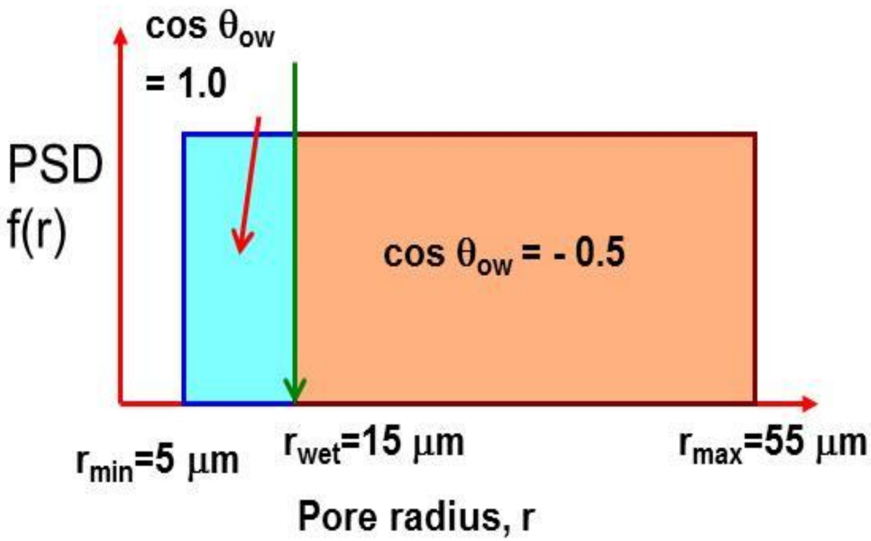
Dale, E.I., and Skauge, A., "Features concerning capillary pressure and the effect on two-phase and three-phase flow," International EAGE - IOR symposium, Timing of IOR to Maximise Production Rates and Ultimate Recovery, Cairo, Egypt, 22 - 24 April 2007.

Holm, R., Kaufmann, R., Dale, E.I., Aanonsen, S.I., Fladmark, G.E., Espedal, M., and Skauge, A.: "Constructing three-phase capillary pressure functions by parameter matching using a modified Ensemble Kalman Filter," *Special Volume in Communications in Computational Physics (CiCP)*: Computational Methods in Energy and Environmental Research, 2008.

Miscible and Immiscible WAG

example

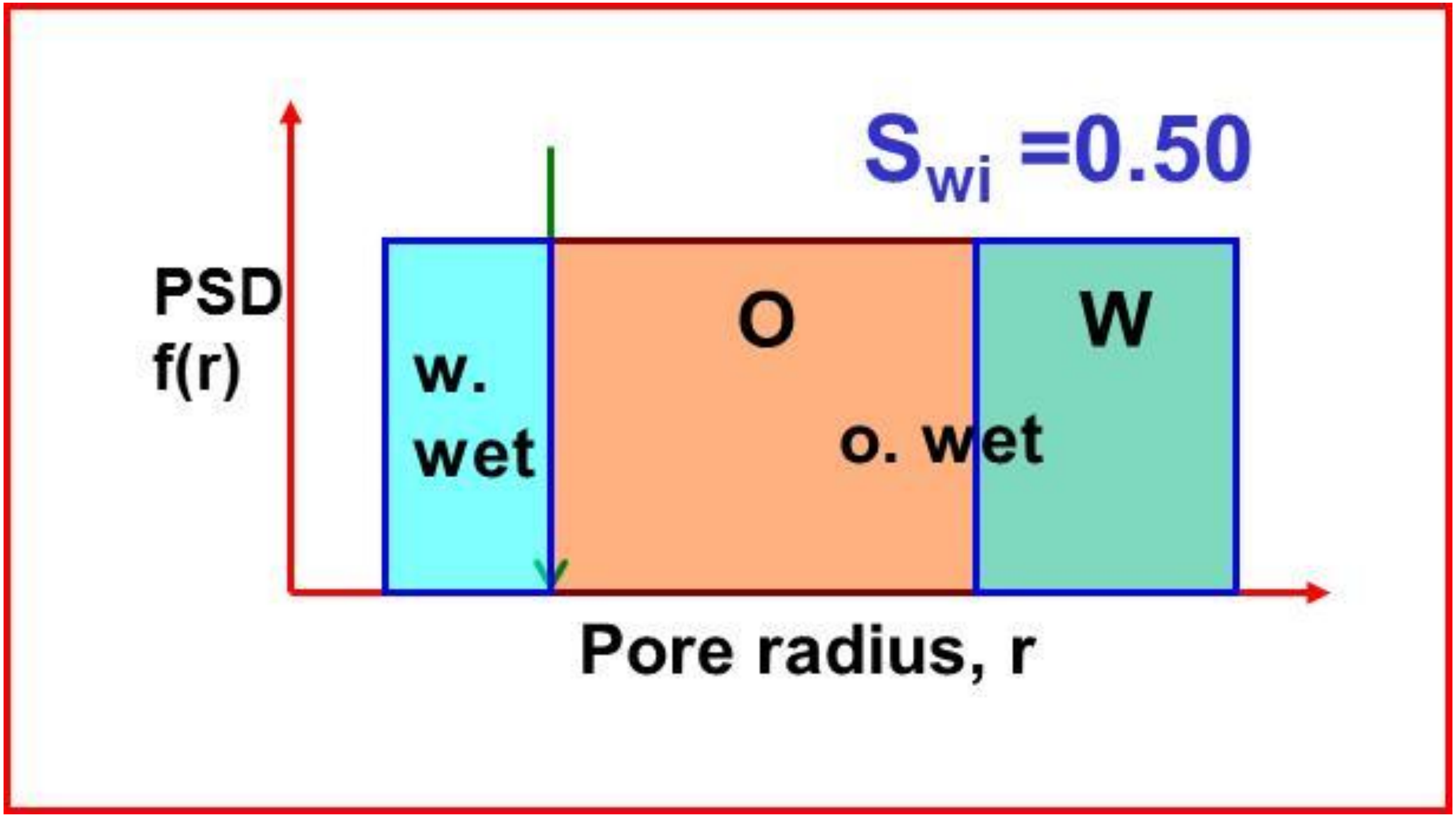
PSD and Wettability



Immiscible and Near miscible IFTs

	IFT	Immiscible	Near-Miscible
	σ_{go}	10	1
	σ_{ow}	15	15
	σ_{gw}	25	16
Spreading coefficient	$C_{s,o}$	0	0

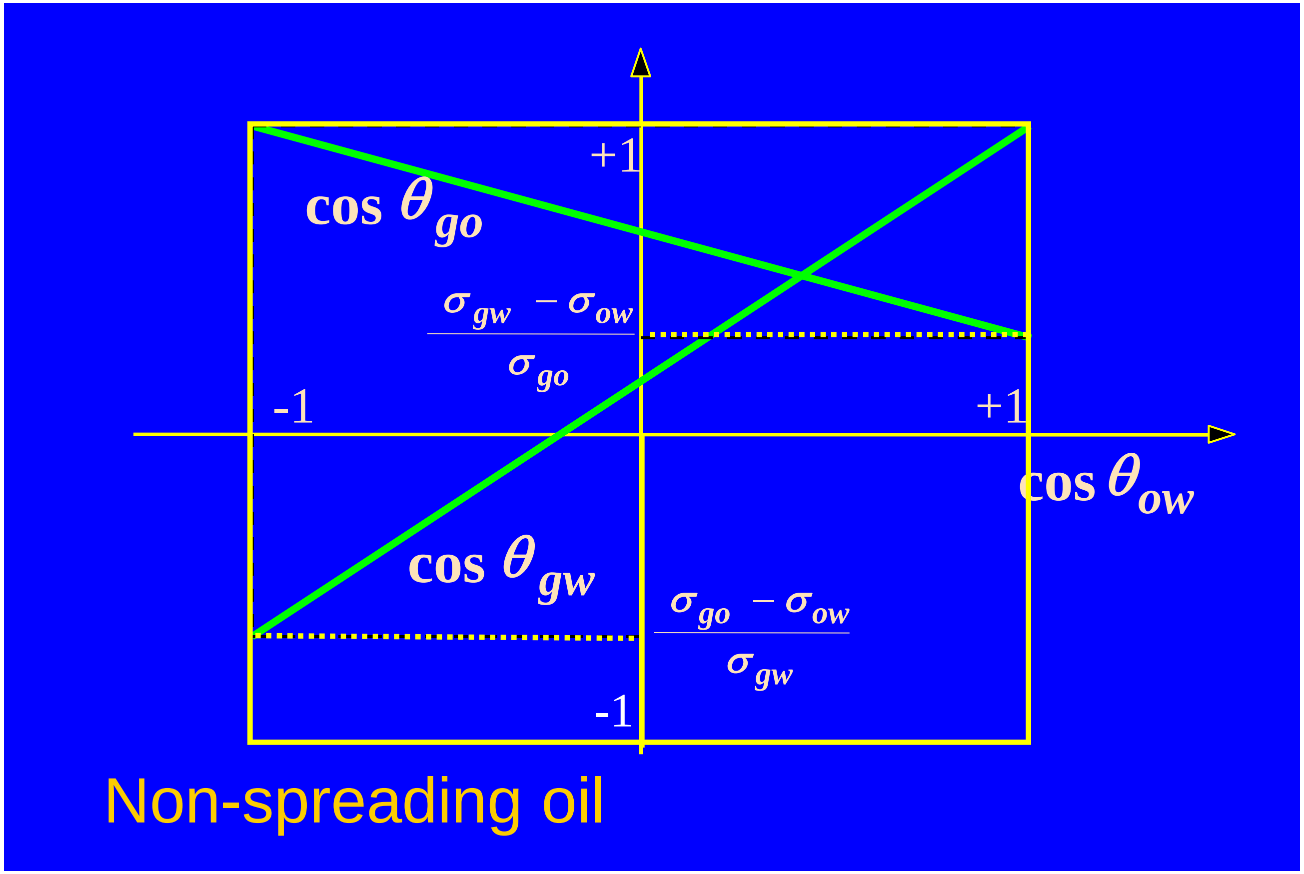
Miscible and Immiscible WAG



WAG started with water injection

Contact angle relations for weakly wetted pores

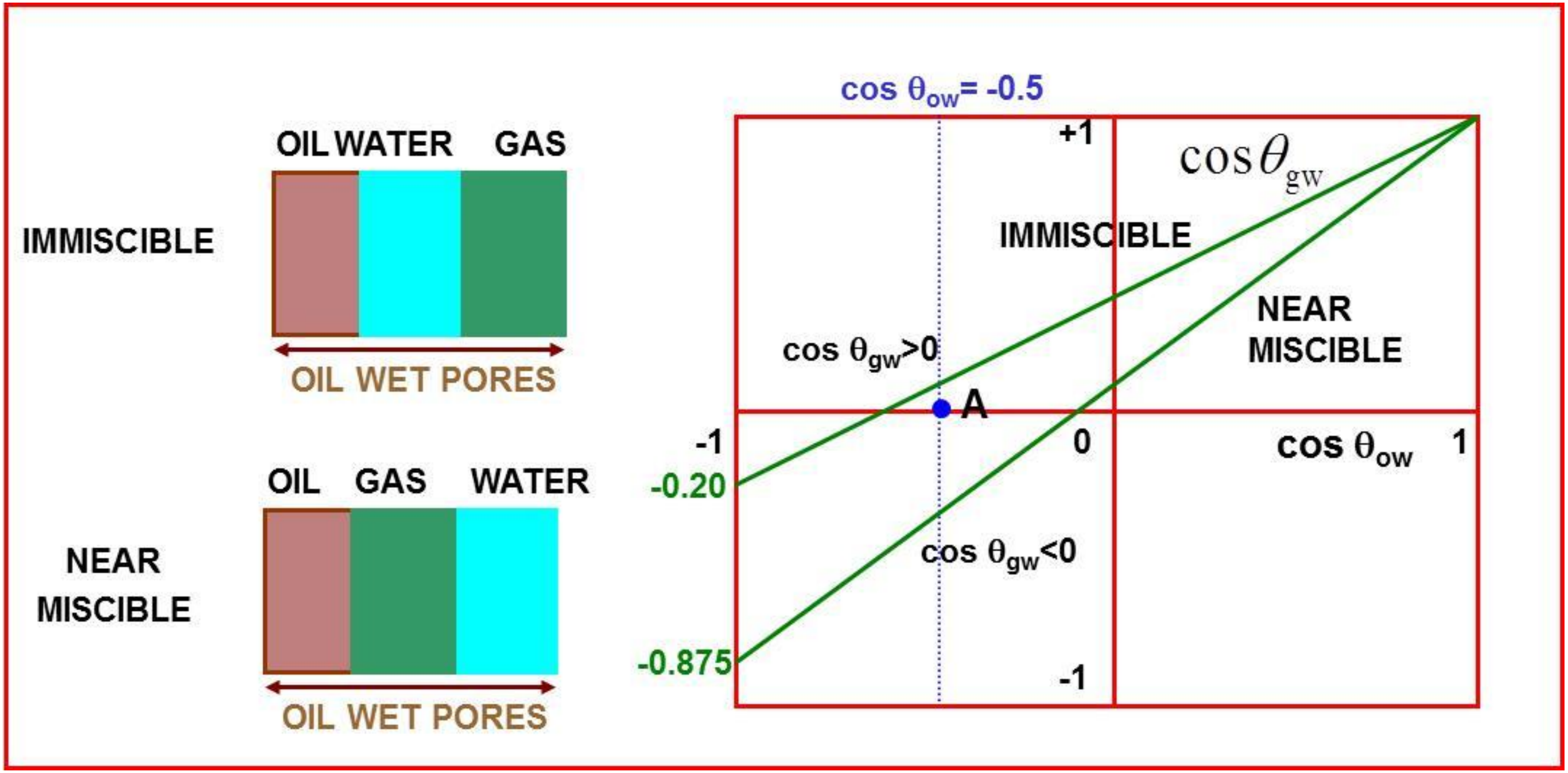
- Linear relations - Non-spreading oil ($C_{S,o}) < 0$



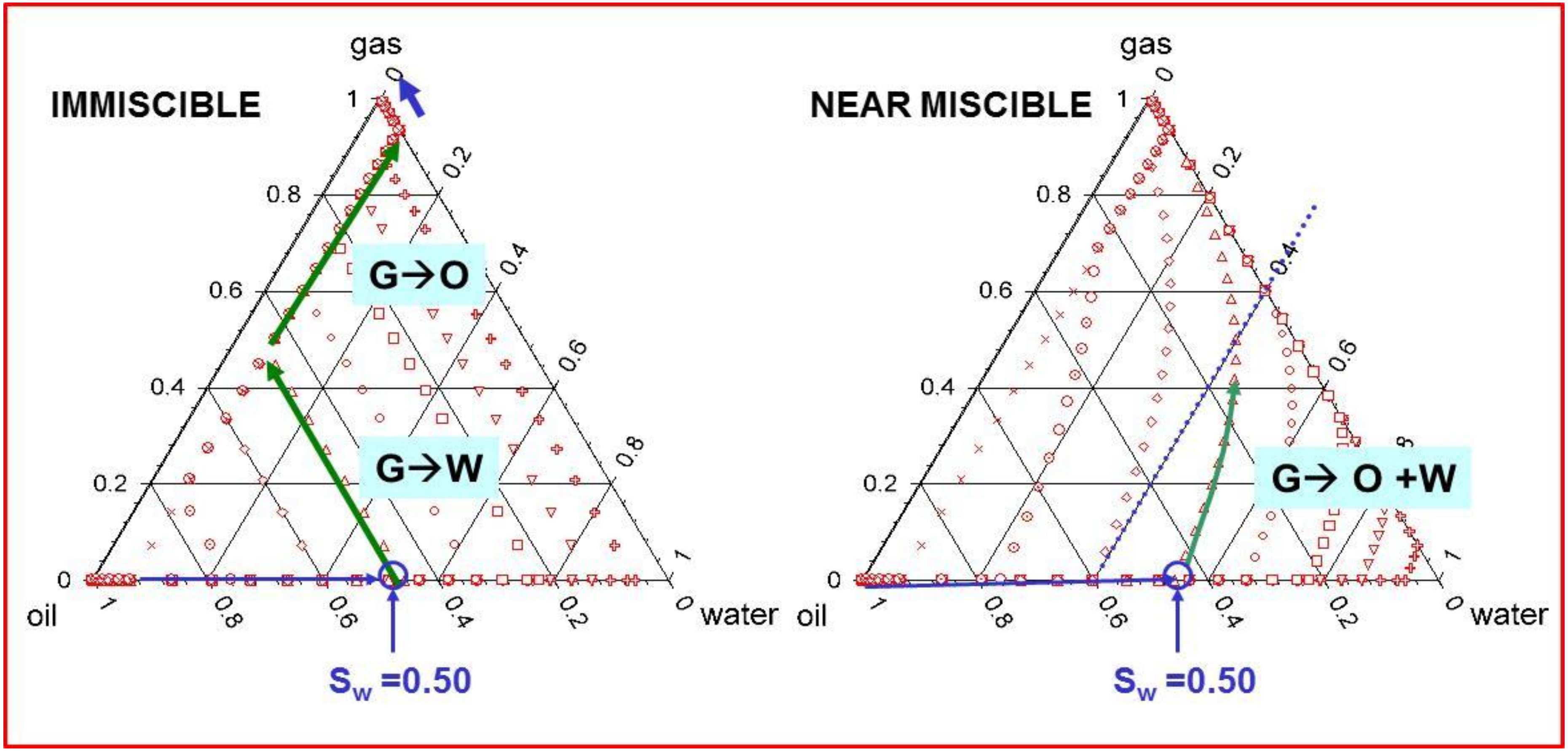
$$\sigma_{gw}\cos\theta_{gw} - \sigma_{go}\cos\theta_{go} - \sigma_{ow}\cos\theta_{ow} = 0$$

Bartell and Osterhof, 1927

Miscible and Immiscible WAG



Miscible and Immiscible WAG



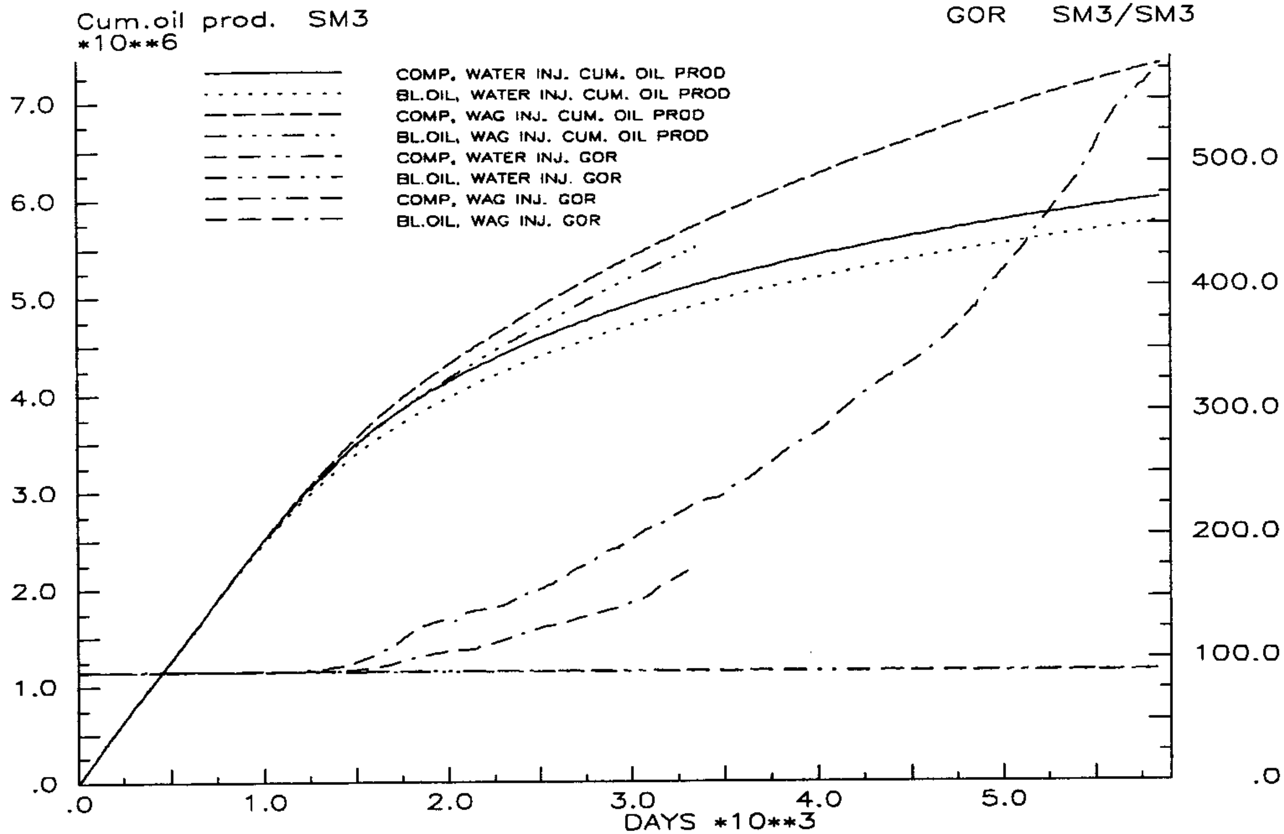


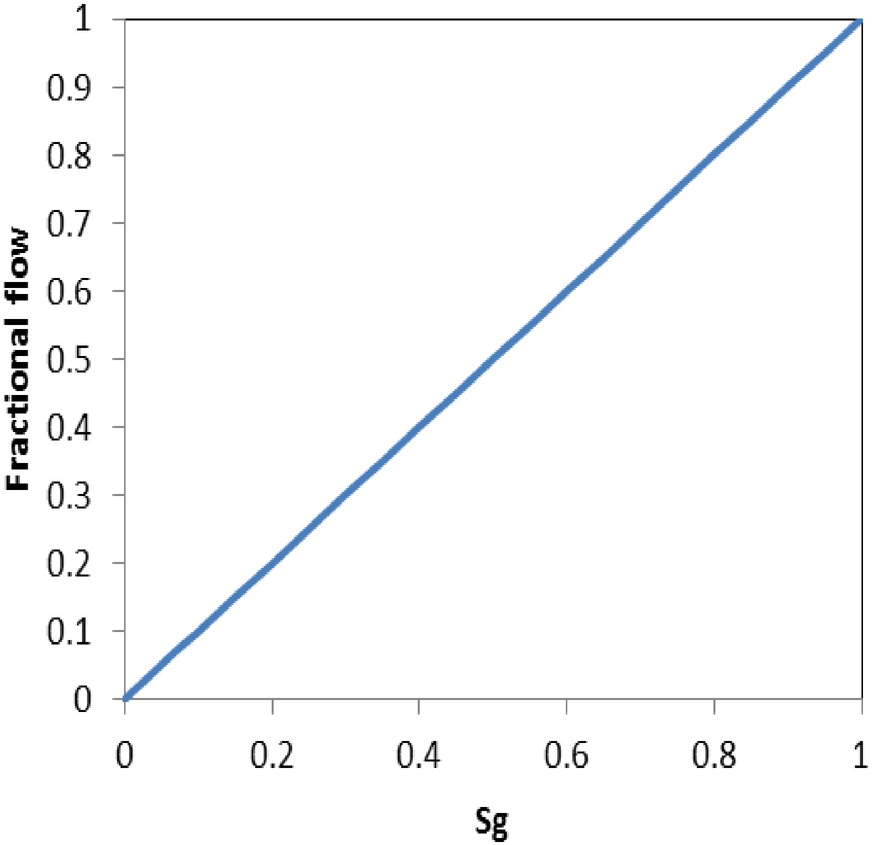
Fig. 5 : BLACK OIL & COMPOSITIONAL MODEL

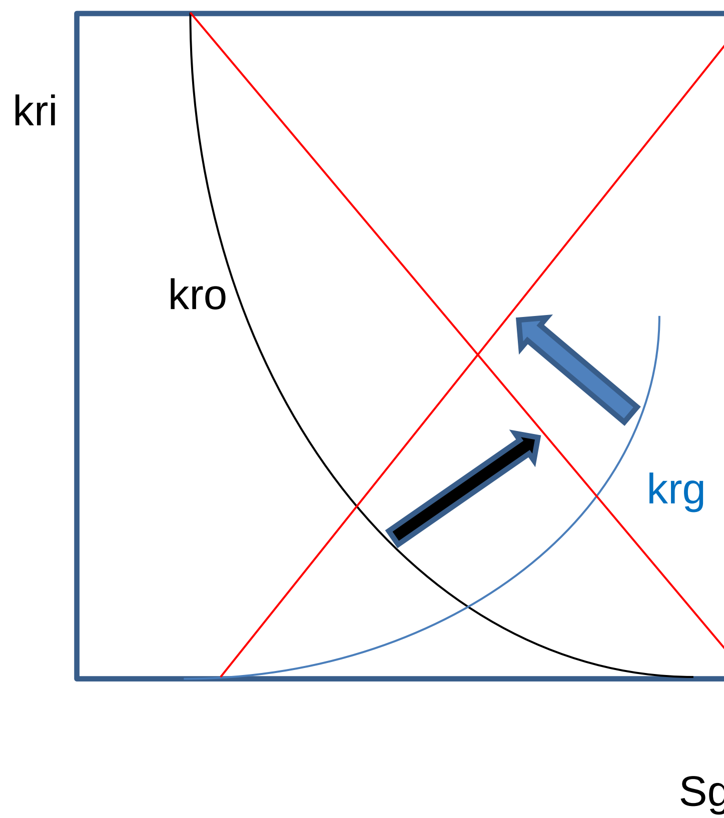
At 9 years	Injection	Oil prod MSm3	Oil Recovery	Watercut	Water inj. MRm3	Gas inj. MRm3	STOIIP MSm3	Res. pres. bar	GOR Sm3/Sm3	Breakthrough/days Water	Gas
Compositional	water	5.15	34.80	0.81	5.42	-	14.8	325	90	750	-
Black oil	water	4.9	33.11	0.81	5.42	-	14.8	325	90	720	-
Compositional	WAG	5.6	37.84	0.65	2.71	2.71	14.8	280	175	750	1250
Black oil	WAG	5.5	37.16	0.69	2.71	2.71	14.8	270	225	720	1400
Compositional	Gas	5.3	35.81	0.43	-	5.42	14.8	262	850	-	850

Table 5 Sector model, water, gas and WAG injection

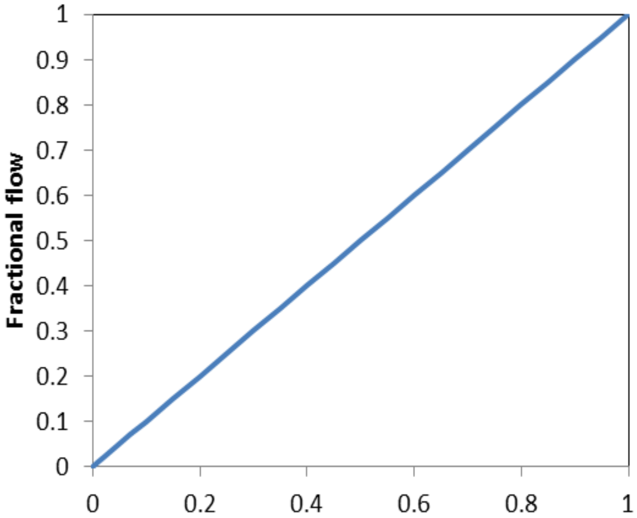
Christensen, J.R., Stenby, E.H., Skauge, A.: "Compositional and Relative Permeability Effects on Near-Miscible WAG," SPE 39627 (1998).

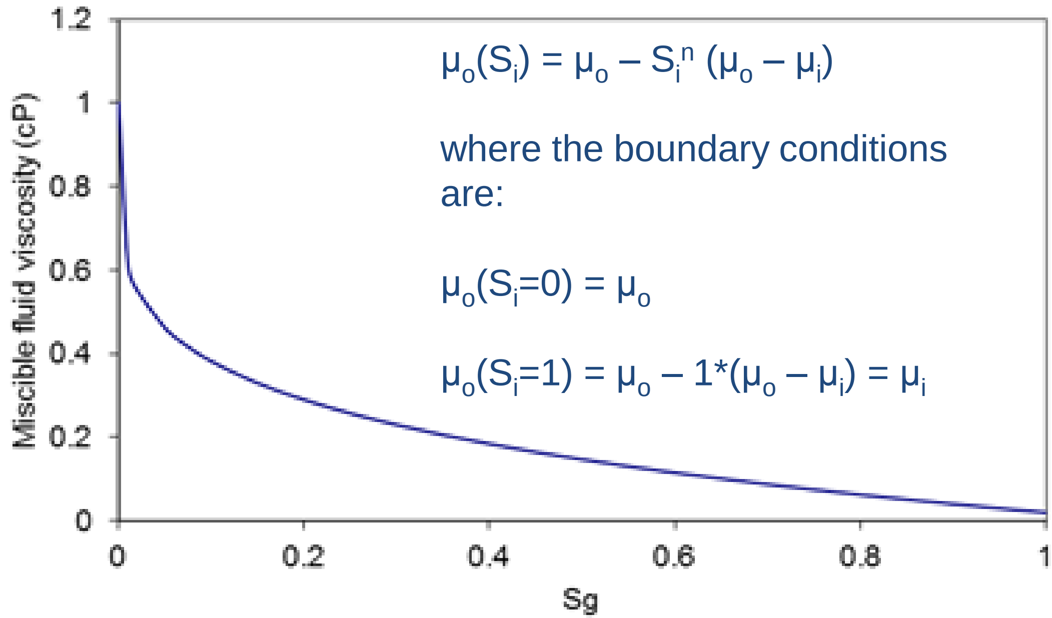
Conversion towards miscible WAG





Miscible WAG at adverse mobility ratio



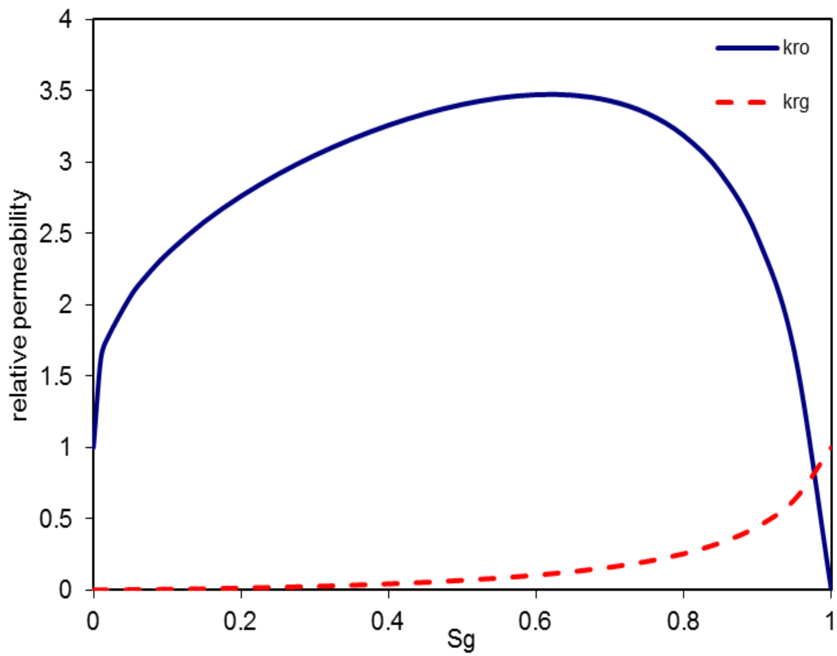


$\mu_o(S_i) = \mu_o - S_i^n (\mu_o - \mu_i)$

where the boundary conditions are:

$\mu_o(S_i=0) = \mu_o$

$\mu_o(S_i=1) = \mu_o - 1^*(\mu_o - \mu_i) = \mu_i$



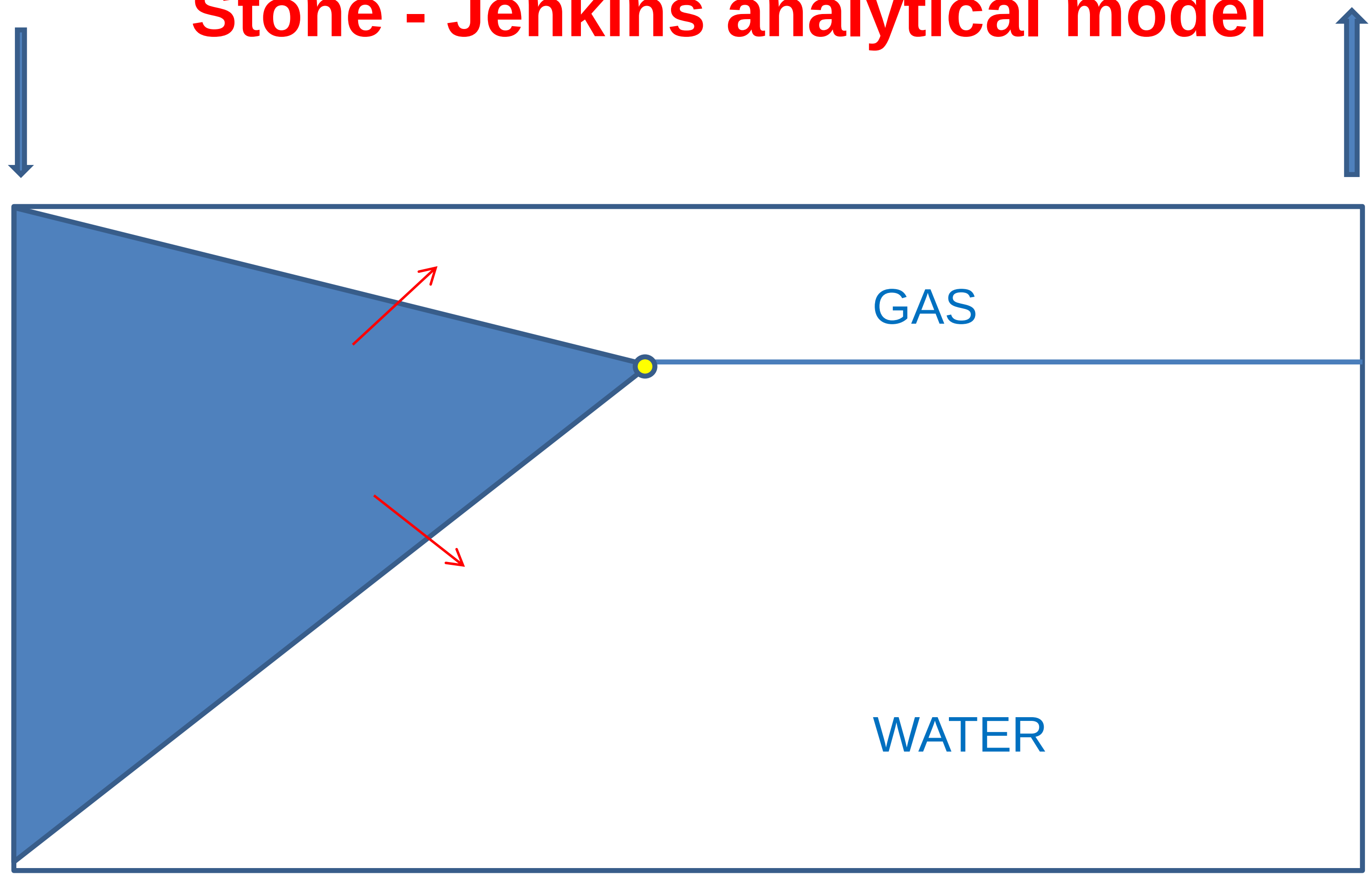
$f_g = S_g$

$k_{ro} = [\mu_o / \mu (S_g)] \cdot (1\text{-}S_g)$

$k_{rg} = [\mu_g / \mu (S_g)] \cdot (S_g)$

Skauge, A., Sorbie, K., Ormehaug, P.A., and Skauge, T., Experimental and Numerical Modeling Studies of Viscous Unstable Displacement, 2009, paper A28, proceedings from Improved Oil Recovery Symposium, Paris, France, April 27-29.

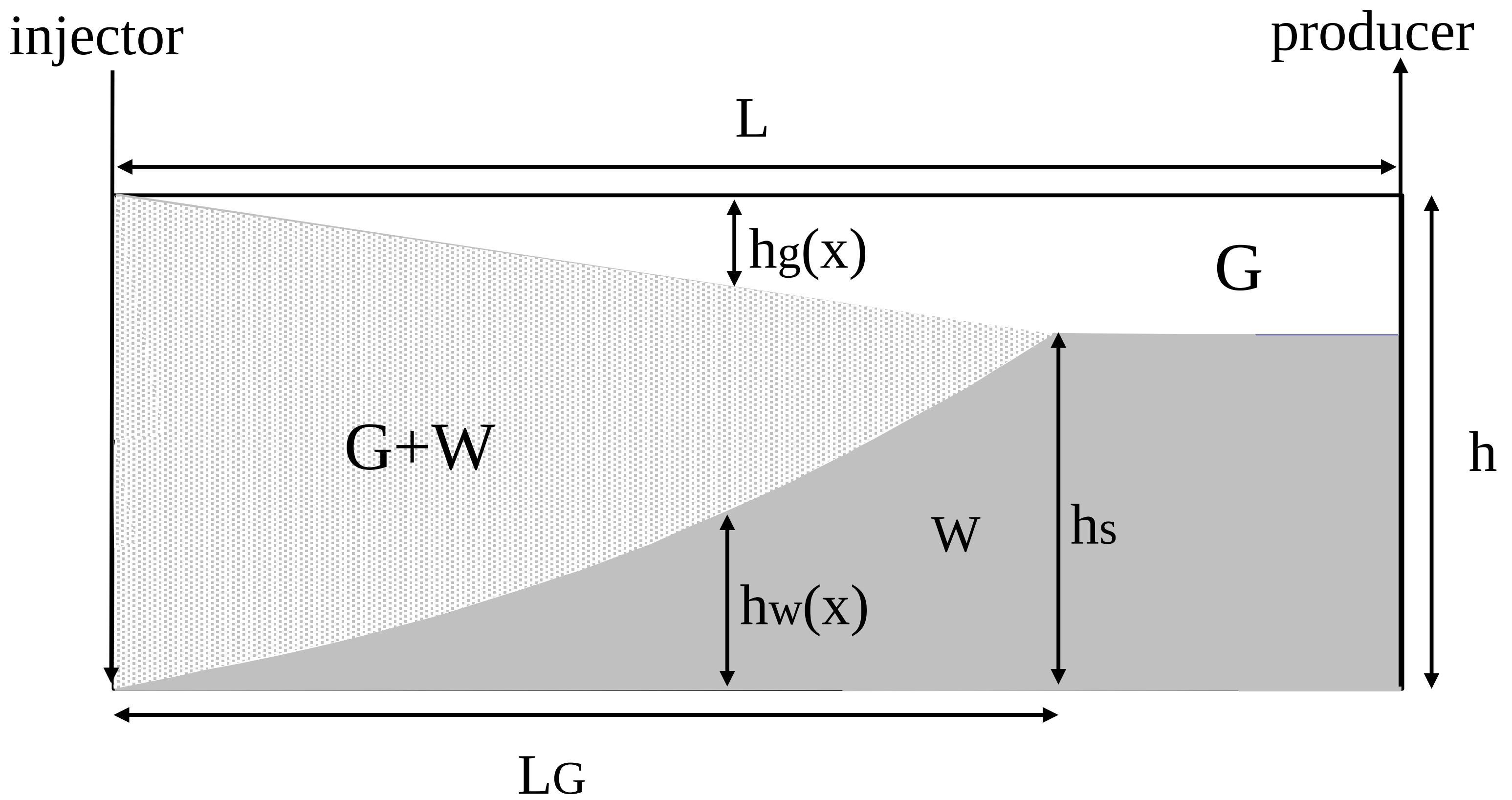
Stone - Jenkins analytical model



Stone - Jenkins

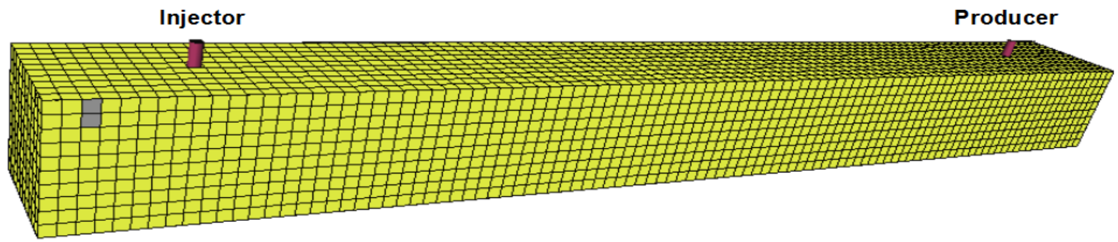
Calculation of extent of the WAG three-phase zone based on two-phase flow only

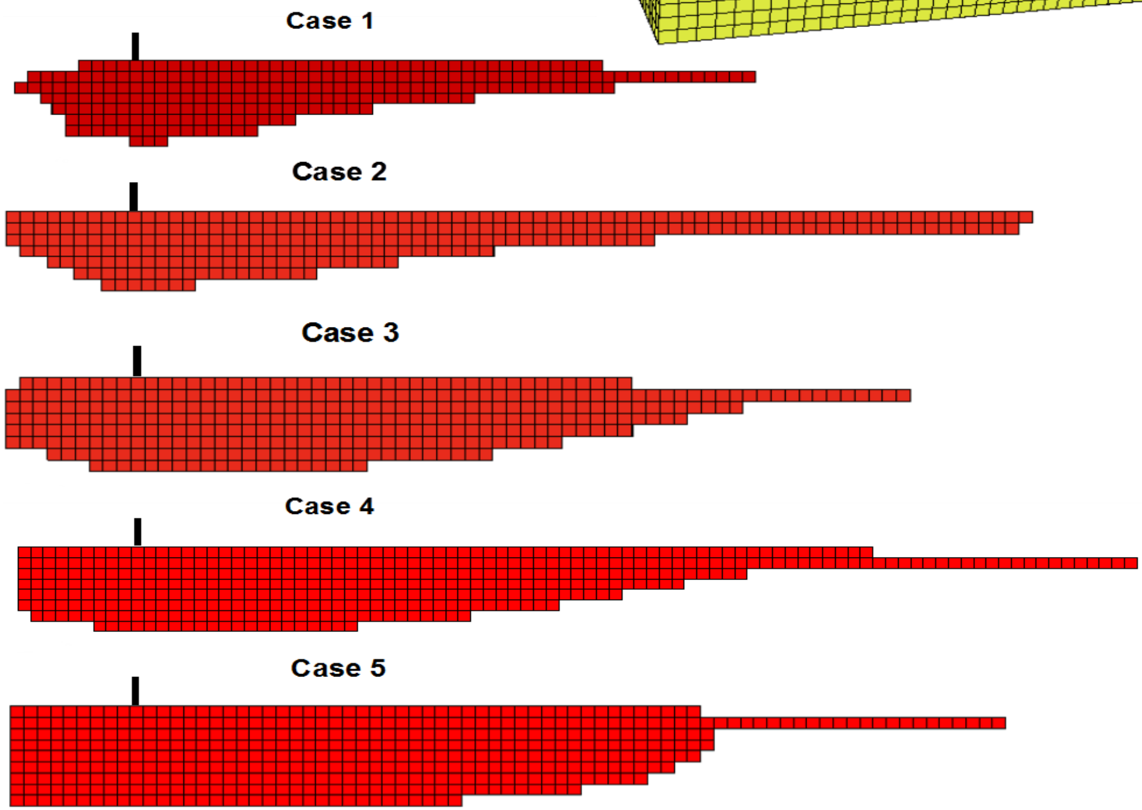
Statement: Jenkins analytical model underestimates the WAG three-phase zone when compared to three-phase flow simulation results



BUT Som (3ph) << Sor (2 ph)

Miscible and Immiscible WAG





Case 1: only 2-*phase rel perm*

Case 2: 2-phase rel perm including Pc

Case 3: 3-phase rel perm hysteresis and gas trapping

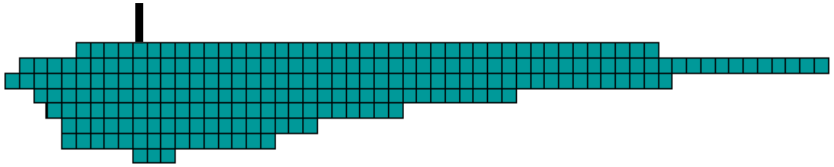
Case 4: 3-phase rel perm hysteresis and gas trapping including Pc

Case 5: 3-*phase rel perm hysteresis and gas trapping including Pc and the effect of Pc on rel perms*

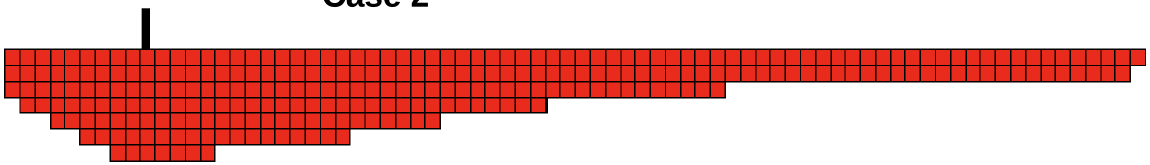
Three-phase zone

Size of three-phase zone is important - Sor may be much lower in the three-phase zone

Case 1

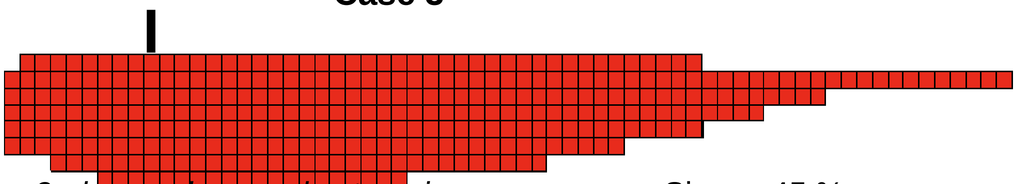


Case 2



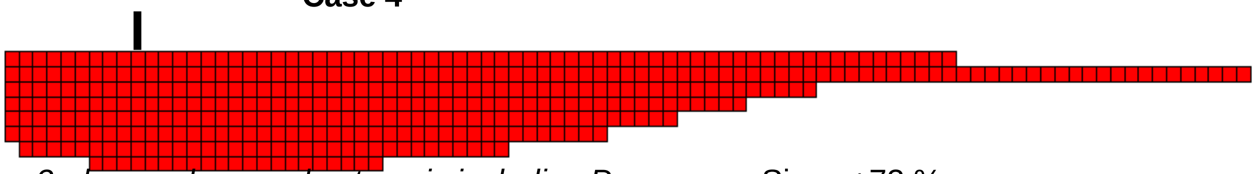
2-phase rel. perm. including Pc Size +19 %

Case 3



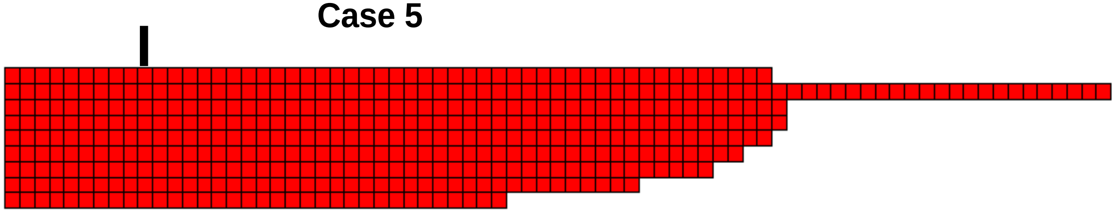
3-phase rel. perm. hysteresis Size +45 %

Case 4



3-phase rel. perm. hysteresis including Pc Size +73 %

Case 5



3-phase rel. perm. hysteresis including Pc and effect of Pc on rel.perm Size +103 %

Recommendations

Gas modelling

Must include information about gas trapping

Gas relative permeability must be able to vary with:

- increasing / decreasing gas saturation
- water saturation
- gas trapping history

Water modelling

Water relative permeability must vary with:

- increasing/decreasing water saturation
- gas saturation

Oil modelling

Residual oil must be allowed to change with trapped gas.

Oil relative permeability should be history dependent.

Summary and Conclusions

WAG processes have been analysed at the pore scale, the core scale and at the reservoir scale.

The observations on different scales are very important for process understanding of both IWAG and nMWAG and for developing consistent reservoir models for simulating these processes.

Core scale relative permeabilities and trapped phase saturation are explained and supported by observations at the pore scale.

The pore scale models are a useful tool to understand trends such as saturation paths in three-phase saturation regions, gas and water phase hysteresis etc.

Summary and Conclusions 2

Three-phase relative permeabilities in WAG processes are significantly reduced compared to two-phase relative permeability due to trapped phases and displacing phase (gas) diversion resulting in more disconnected saturation regions.

The micromodel observations clearly show that trapped gas in IWAG processes leads to microscopic diversion of injected gas spreading gas to larger areas with subsequent gas injection cycles and this results in additional oil recovery.

WAG relative permeability will be saturation history dependent due to gas trapping and its impact on residual oil saturation and phase mobilities.

Simulation of core flood experiments using three-phase relative permeability hysteresis greatly improves the match to IWAG core floods.

Investigation into improved oil recovery by WAG should consider a WAG process design seeking to maximize the trapped gas saturation and greatly extend the zone of 3 phase flow in the reservoir.

Summary and Conclusions

Field case simulations have shown higher oil recovery and later gas breakthrough when the three-phase hysteresis relative permeability and saturation history dependent approach was used.

A set of recommendations for field IWAG and nMWAG applications is made above which is directly informed by the pore and core scale observations.

The intention of the paper is to review and link together recent development in our understanding of the mechanisms of both immiscible and miscible /near miscible WAG processes.

We hope that we have shown how the pore scale physics and core scale observations are linked to and can explain the field scale oil recovery mechanisms in IWAG, MWAG and nMWAG.

Thank you for listening