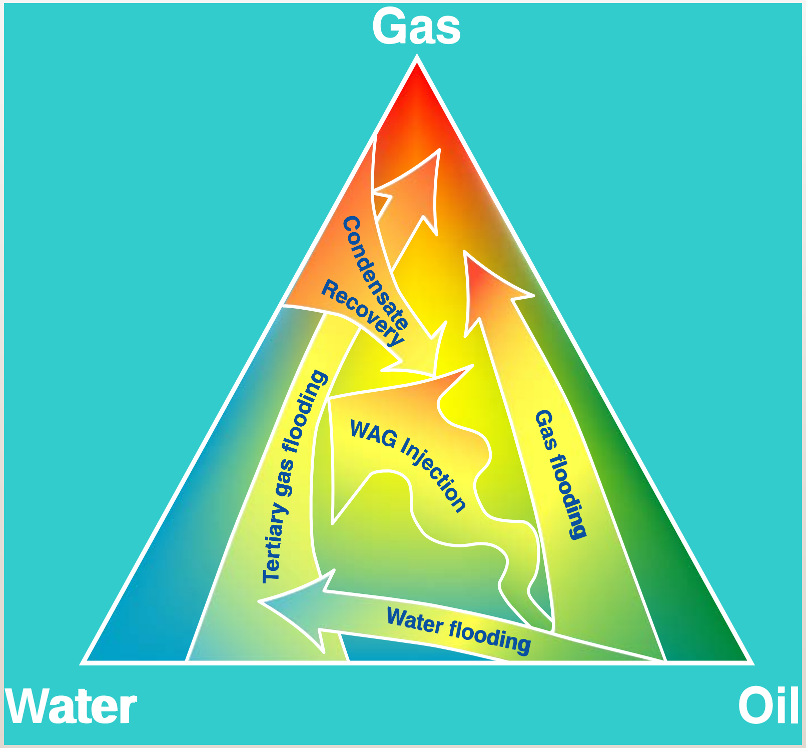
New Three-Phase Modeling Capabilities in Eclipse



PhD meeting

NTNU

7th February, 2008

by

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Gas Based Recovery Methods

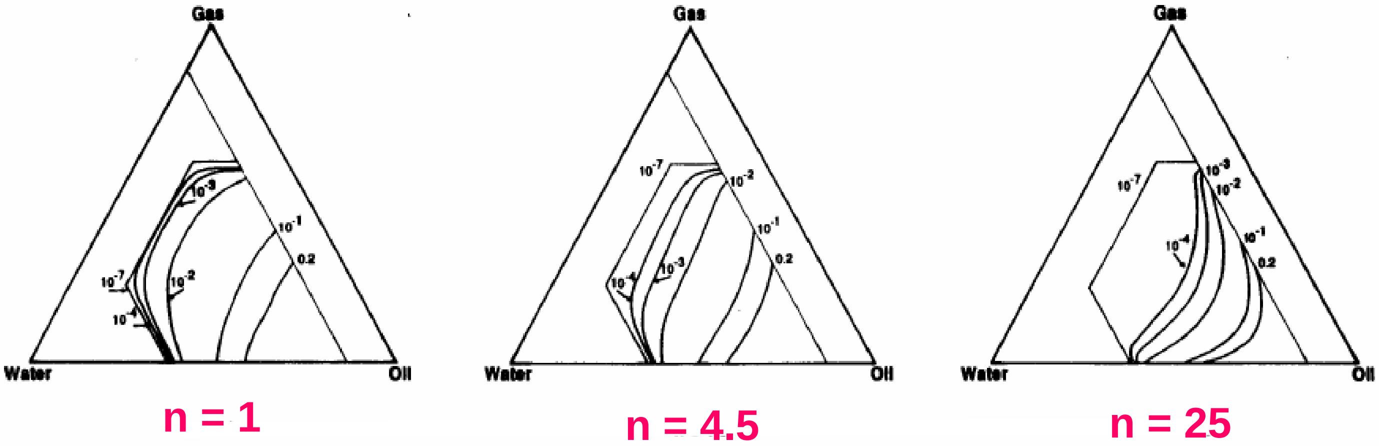
StatoilHydro

Outline

- Extensions to Stones first model (SPE 24116)
  - Available in Eclipse version 2008_1
- The ODD3P model option
  - Available in Eclipse version 2007_1, immiscible option
  - Available in Eclipse version 2008_1, miscible option

Modifications to Stone's first model
Introducing the n-exponent

Oil isoperms for various exponent values



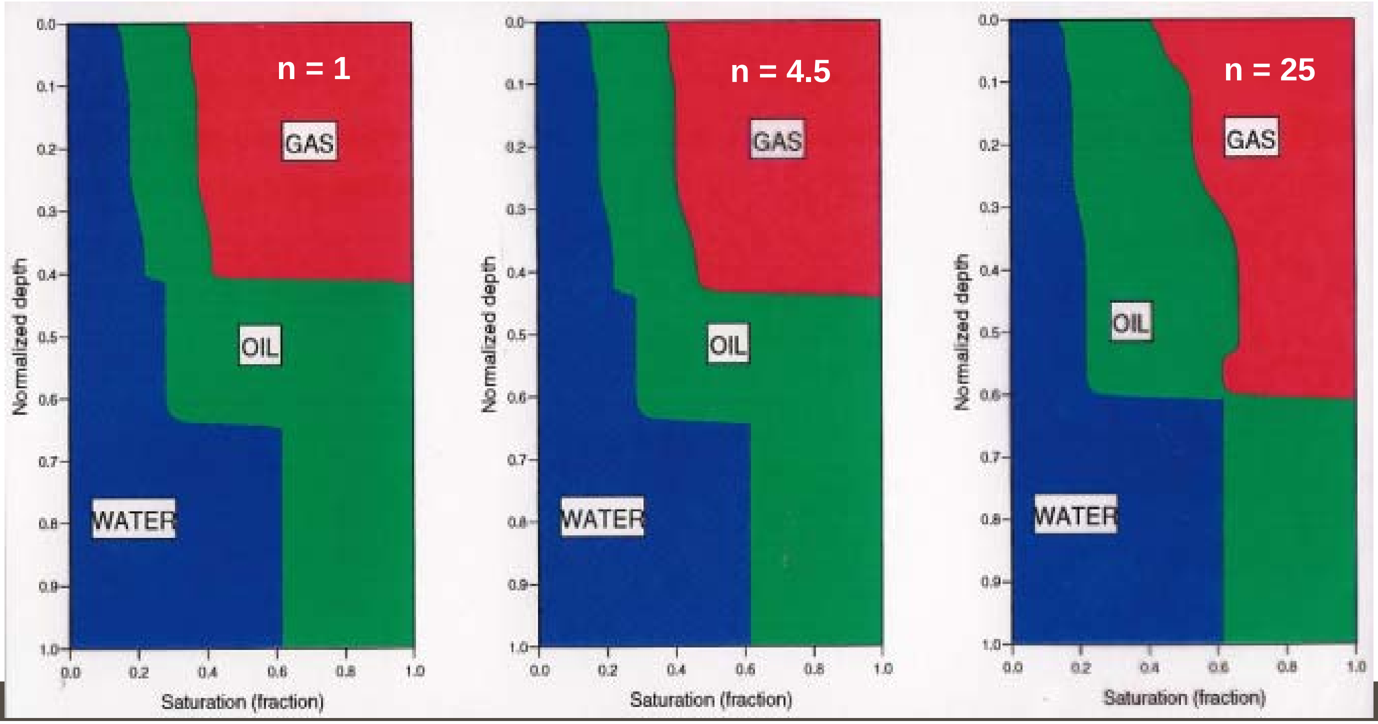
Modified first model of Stone

$$k_{ro} = \frac{k_{row}(S_w)\ k_{rog}(S_g)}{k_{rocw}} \left[\frac{S_o^*}{(1-S_w^*)\ (1-S_g^*)} \right]^n$$

SPE 24116

Exponent's impact on saturation distribution during flow

- Low exponent value keeps oil between gas and water
- High exponent value causes gas to bypass oil
- This exponent parameter will appear in the 2008 version of Eclipse as a gridblock and directional dependent parameter



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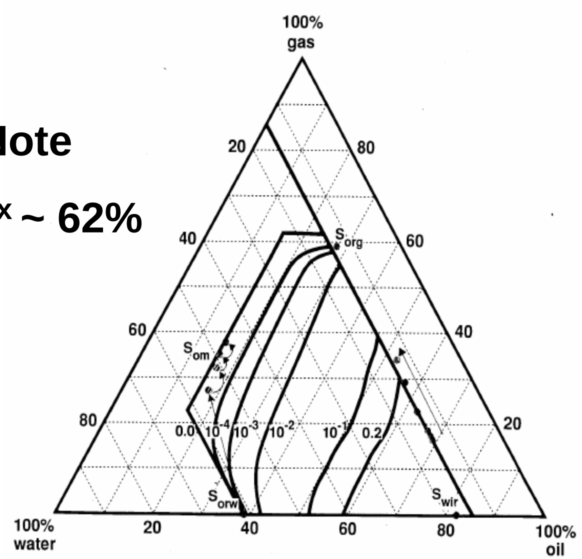
Modifications to Stone's first model sufficient for modeling equilibrium gas injection

- Exponent value of 4 was sufficient to match oil recovery curve
- Oil iso-curves are more linear in compliance with Oak et al. (*JPT*, Aug. 1990)

Note

$S_g^{max} \sim 62\%$

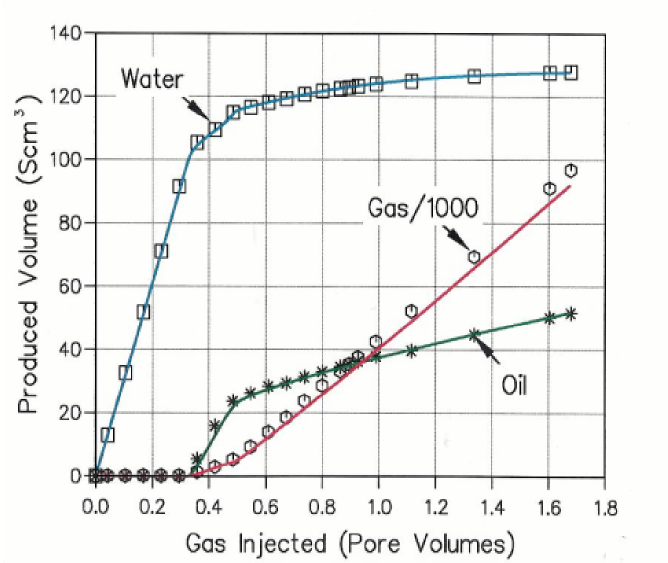
ROCK CURVE OIL ISOPERMS (n=4) AND RESIDUAL OIL SATURATIONS



MODIFIED FIRST MODEL OF STONE

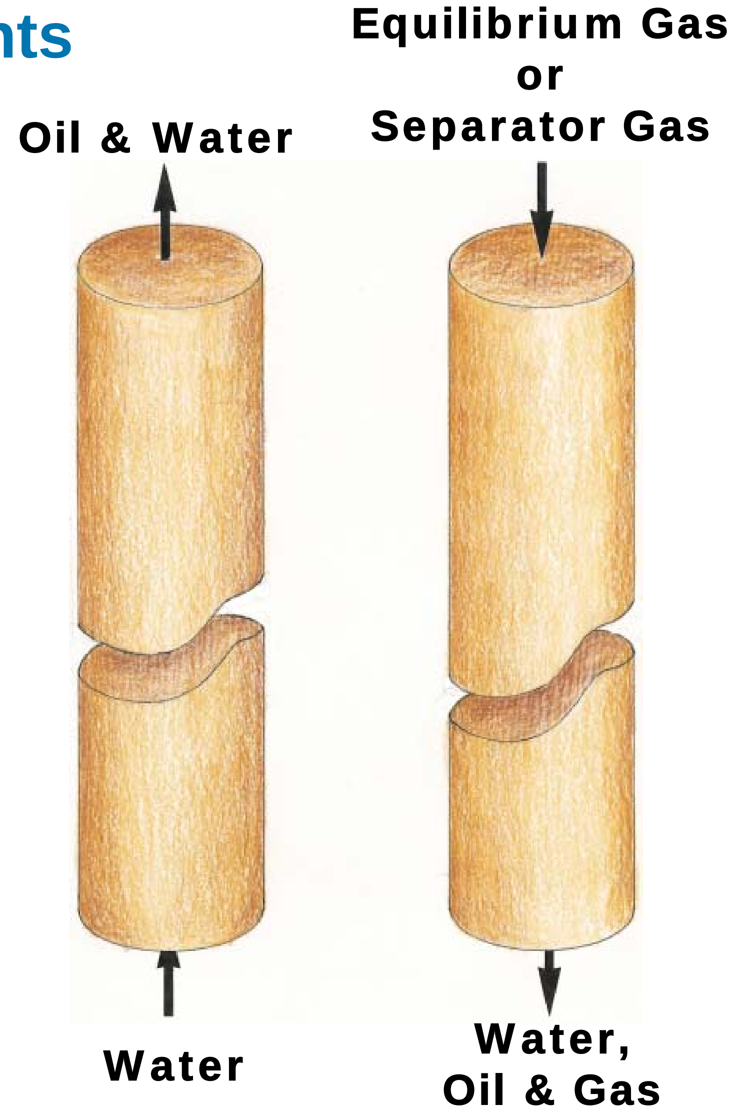
$$k_{ro} = \frac{k_{row}(S_w)k_{rog}(S_g)}{k_{rocw}}\left[\frac{S_o^*}{(1-S_w^*)\ (1-S_g^*)}\right]^n$$

Simulated and experimental recoveries of Experiment 1



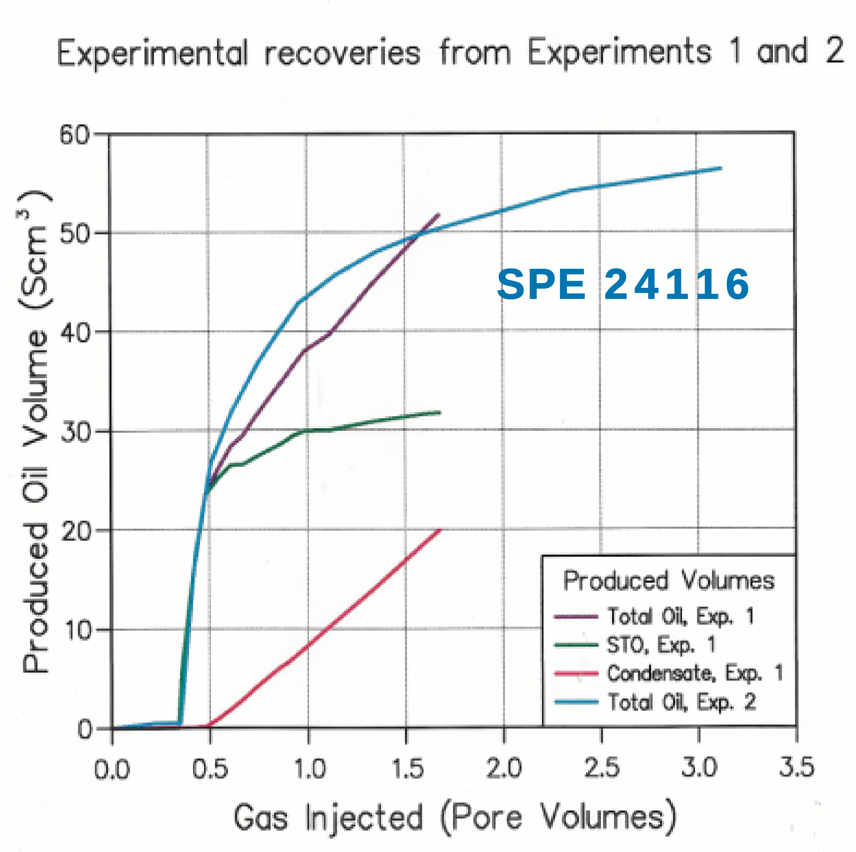
Tertiary gas displacement experiments

- Vertical 1.2 m long Bentheimer Core, water-wet condition
- Gas injection from top of core after water injection from below
  1) Equilibrium gas
  2) Dry separator gas
- Oil's bubble point at 313.5 bar and 91.9 °C
  – B_o=1.62
  – GOR=200.9
  – μ_o=0.43 cP
  – σ_{go}=1.2 mN/m



Some conclusions from experiments

- Significant phase behavior effects from vaporization
- Long after drainage, oil still draining at end of experiments
- Modeling flash process from reservoir to ambient conditions important for proper fluid description
- Capillary pressure and relative permeability are important parameters when modeling experiment

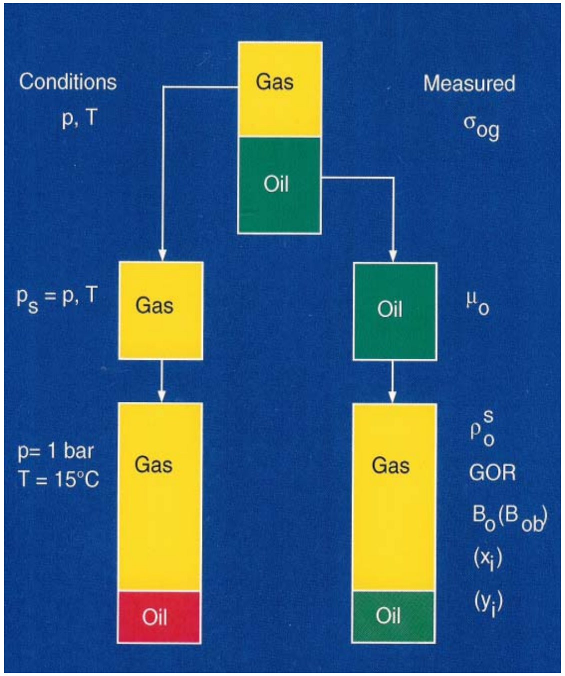


The flash process

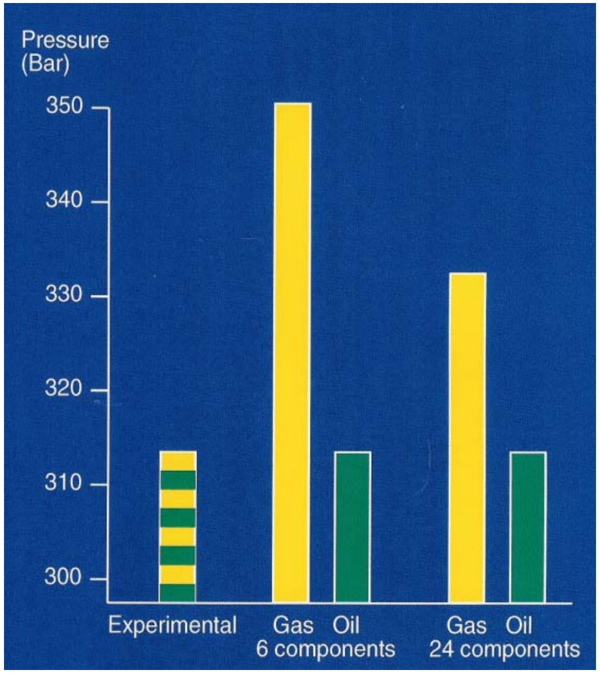
SPE 24116

- Sufficient number of pseudo-components are required for proper molecular weight representation (composition) in modeling gas injection with an Equation-of-state (EOS)
- If too few pseudo-components are used in an EOS model, significant errors in modeling saturation pressure may occur

Flash Procedure



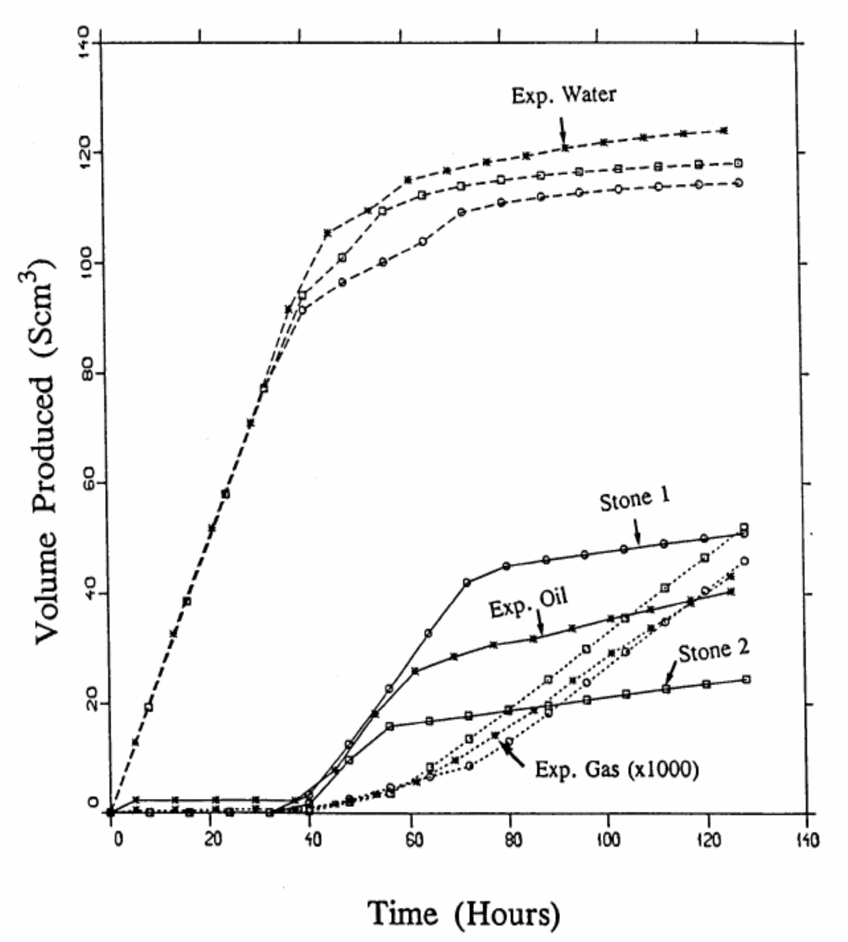
Saturation Pressure



Preliminary simulations using Stone's models

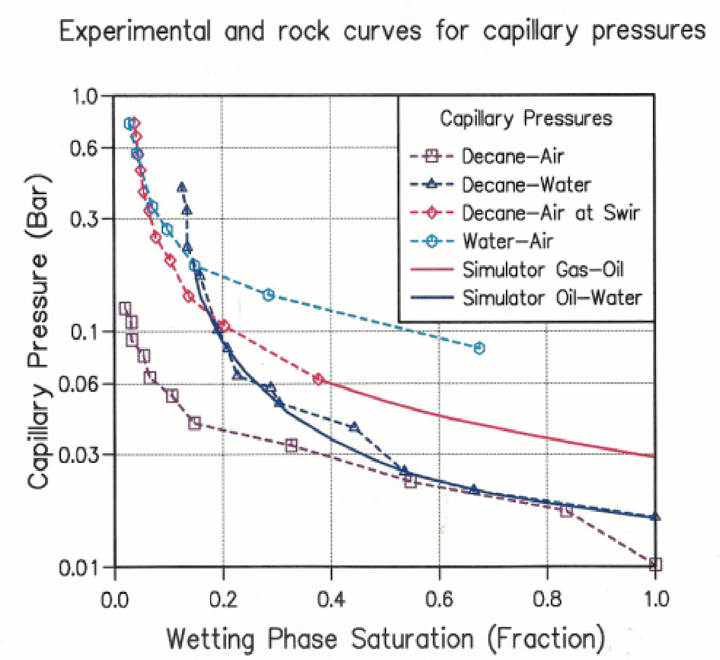
Equilibrium Gas Injection

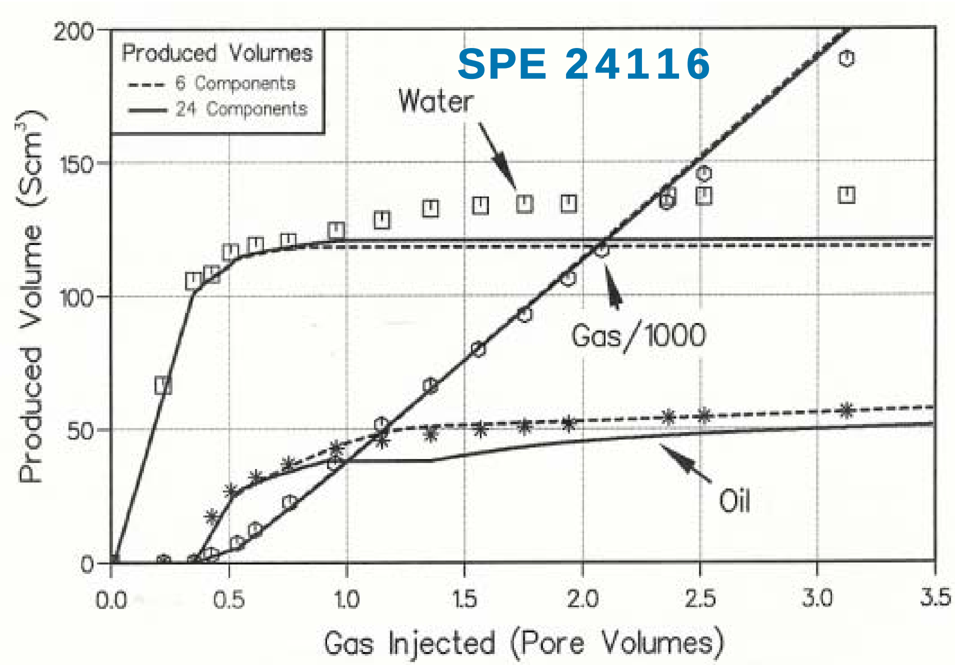
- Modification required to Stone model
- Water recovery profile proved most difficult to history match



Modifications to Stone's first model insufficient for modeling dry gas injection

- Water recovery not properly modeled for dry gas injection experiment
- Vaporization impacts capillary forces which are not properly represented
- Correct modeling of maximum gas saturation remain a challenge



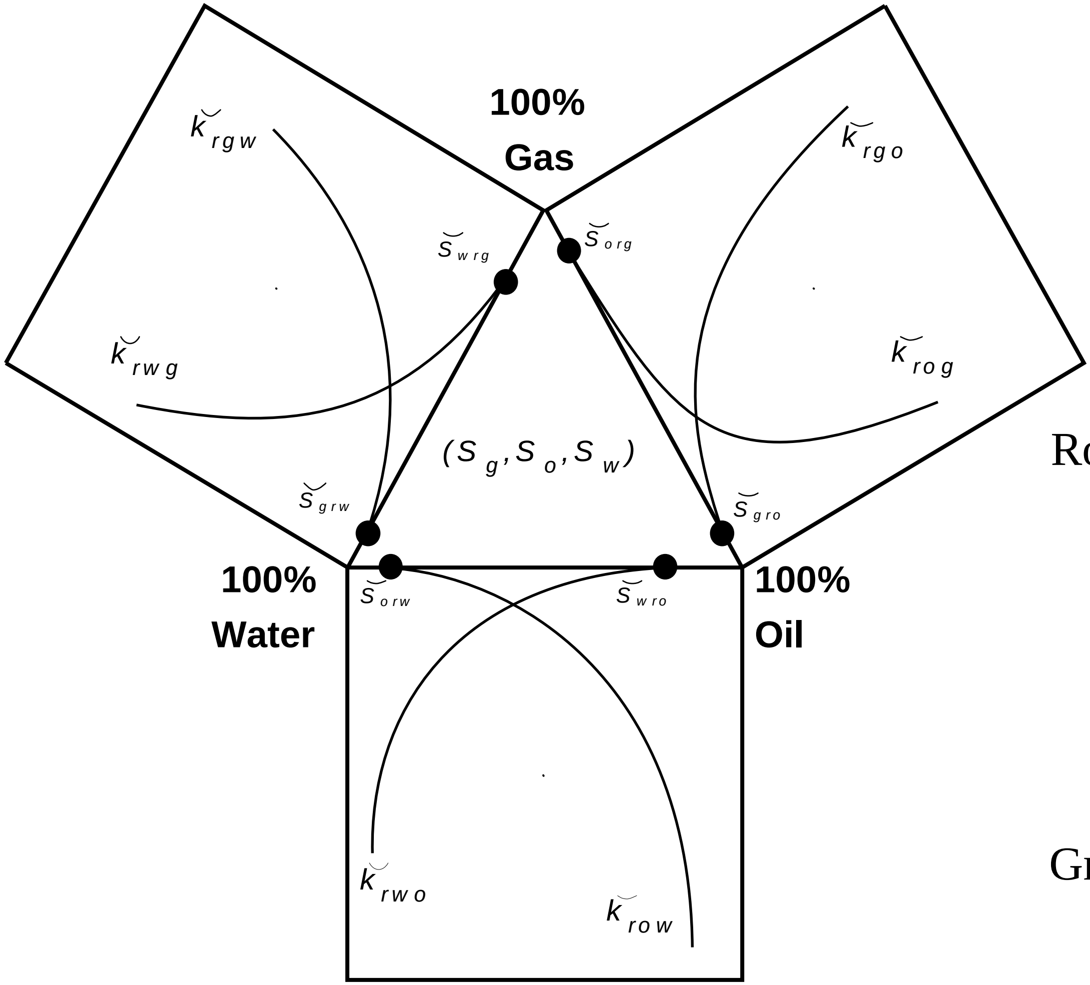


ODD3P three-phase model option

- Developed to extend Stone's water-wet three-phase models
- The ODD3P model extends the capability to handle other wetting conditions through each three-phase property being dependent on two two-phase properties
- The ODD3P model is an extension to the IKU3P model option in compositional Eclipse
  - Relevant papers: SPE 74705, SPE 75138 and *RUTH Program Summary* book
  - Three-phase properties are now consistent at all two-phase boundaries
  - Couples capillary pressure and relative permeability through saturation
    - $k_{ri} = f\left[S_i\left(P_c\right)\right]$
  - Primary, secondary and tertiary process data may be applied
  - Dynamic gridblock dependent end-point saturations for all processes
  - Hysteresis capability (for three sets of two-phase data)
  - miscibility capability

SPE 74705

ODD3P model concept



Model Input – Two-Phase Data

Rock Type (Table) data

$$\breve{S}_w = \breve{S}_w\left(P_{cow}\right); \qquad \breve{S}_g = \breve{S}_g\left(P_{cgo}\right)$$

$$\breve{k}_{row} = \breve{k}_{row}\left(\breve{S}_w\right); \qquad \breve{k}_{rgo} = \breve{k}_{rgo}\left(\breve{S}_g\right)$$

$$\breve{k}_{rwo} = \breve{k}_{rwo}\left(\breve{S}_w\right); \qquad \breve{k}_{rog} = \breve{k}_{rog}\left(\breve{S}_g\right)$$

Gridblock Data

$$\bar{S}^r_{gro}, \bar{S}^r_{grw}, \bar{S}^r_{org}, \bar{S}^r_{orw}, \bar{S}^r_{wrg} \text{ and } \bar{S}^r_{wro}$$

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Eclipse keywords in PROPS section

- ODD3P
  - Specifies to use model
- EPSODD3P
  - Specifies end-point saturation scaling preference, reference and threshold values for interfacial tension and capillary number
- PCODD3P, PCODD3PW & PCODD3PG
  - Specifies the capillary pressure and saturation calculation control parameters
- PSORG, PSGRO, PSORW, PSWRO, PSGRW & PSWRG
  - Primary end-point saturations for gridblocks
- HSORG, HSGRO, HSORW, HSWRO, HSGRW & HSWRG
  - Hysteresis end-point saturations for gridblock

Eclipse keywords in REGIONS section

- PSTNUM, ISTNUM & DSTNUM
  - Primary, increasing (water) and decreasing saturation table numbers
- SDROG, SDRGO, SDROW, SDRWO, SDRGW & SDRWG
  - Initial gridblock direction saturation indicators

Eclipse keywords in SOLUTION section

- DBGODD3P
  - Debugging information

Eclipse keywords in SUMMARY section

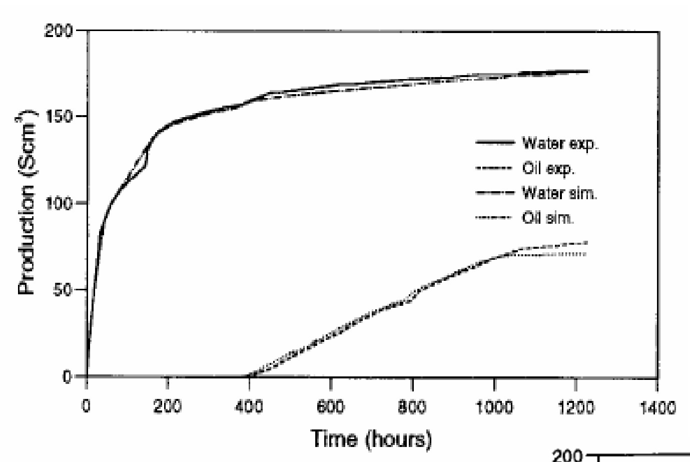
- BSDROG, BSDRGO, BSDROW, BSDRWO, BSDRGW & BSDRWG
  - Gridblock phase saturation direction indicators
- BSGNRM, BSONRM & BSWNRM
  - Gridblock normalized saturations
- BSOGTN, BSGOTN, BSOWTN, BSWOTN, BSGWTN & BSWGTN
  - Gridblock turning point saturations
- BSOGNH, BSGONH, BSOWNH, BSWONH, BSGWNH & BSWGNH
  - Gridblock hysteresis normalized saturations
- BSOGNE, BSGONE, BSOWNE, BSWONE, BSGWNE & BSWGNE
  - Gridblock equivalent opposite direction normalized saturations
- BSORGB, BSGROB, BSORWB, BSWROB, BSGRWB & BSWRGB
  - Residual saturations to calculate normalized saturations

Eclipse keywords in SUMMARY section cont.

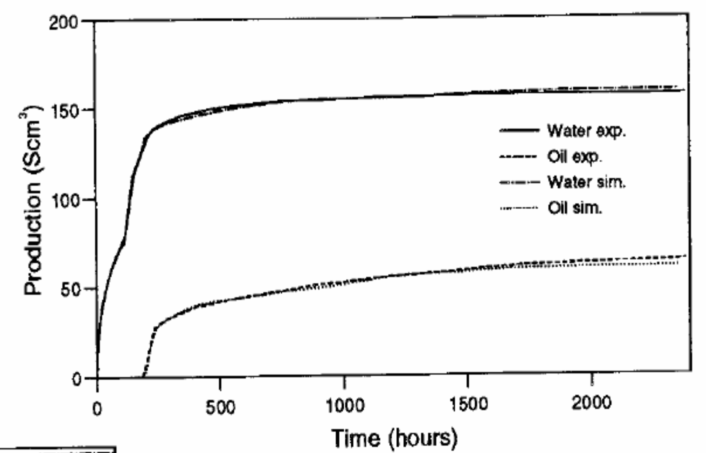
- BSORGP, BSGROP, BSORWP, BSWROP, BSGRWP & BSWRGP
  - Process dependent residual saturations
- BIFTGO, BIFTWO & BIFTGW
  - Gridblock interfacial tension values
- BKROGN, BKRGON, BKROWN, BKRWON, BKRGWN & BKRWGN
  - Gridblock representative relative permeability
- BKROGH, BKRGOH, BKROWH, BKRWOH, BKRGWH & BKRWGH
  - Gridblock turning point relative permeability
- BKROGE, BKRGOE, BKROWE, BKRWOE, BKRGWE & BKRWGE
  - Gridblock equivalent relative permeability
- BKROGT, BKRGOT, BKROWT, BKRWOT, BKRGWT & BKRWGT
  - Gridblock opposite direction turning point relative permeability

Tertiary gas injection recovery, varying wettability

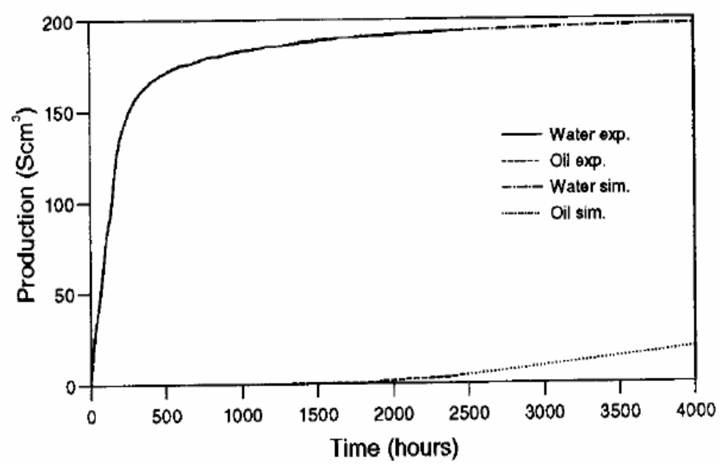
Water-wet



Mixed-wet



Oil-wet



Book:

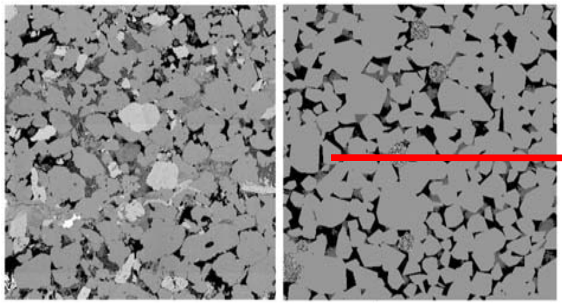
RUTH Program Summary

NPD, Stavanger, 1997

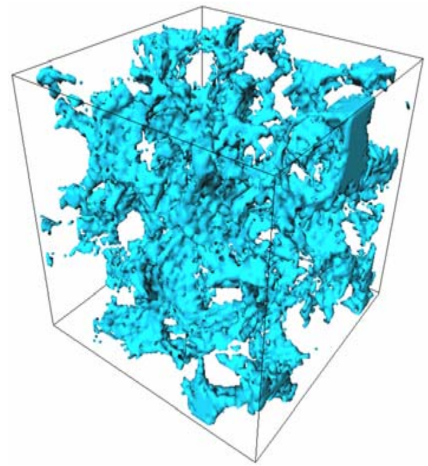
Pore scale modeling (*e*Core)

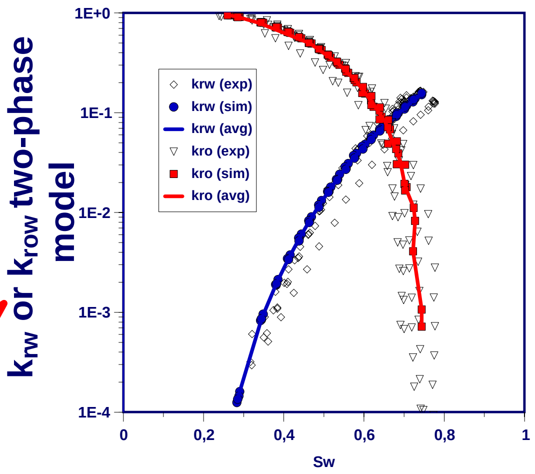
Core-scale multi-phase flow parameters

Thin section

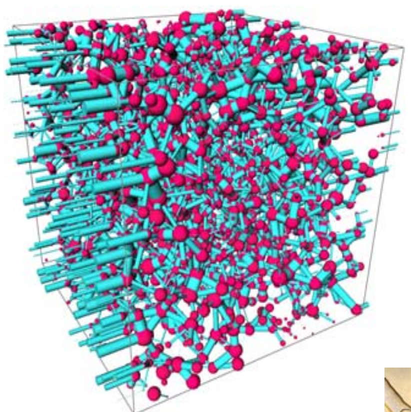


3D pore space



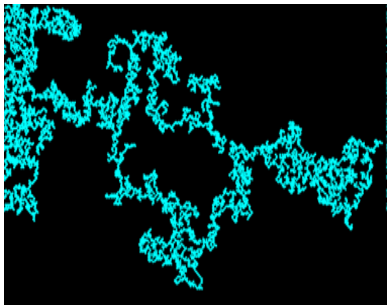


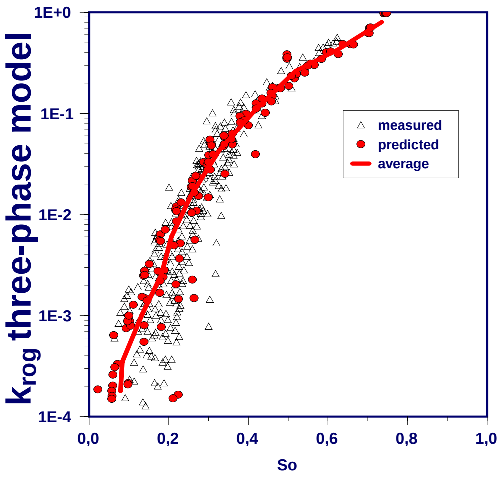
Network model

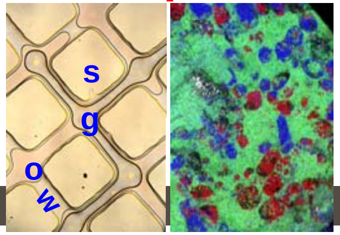


flow

simulation







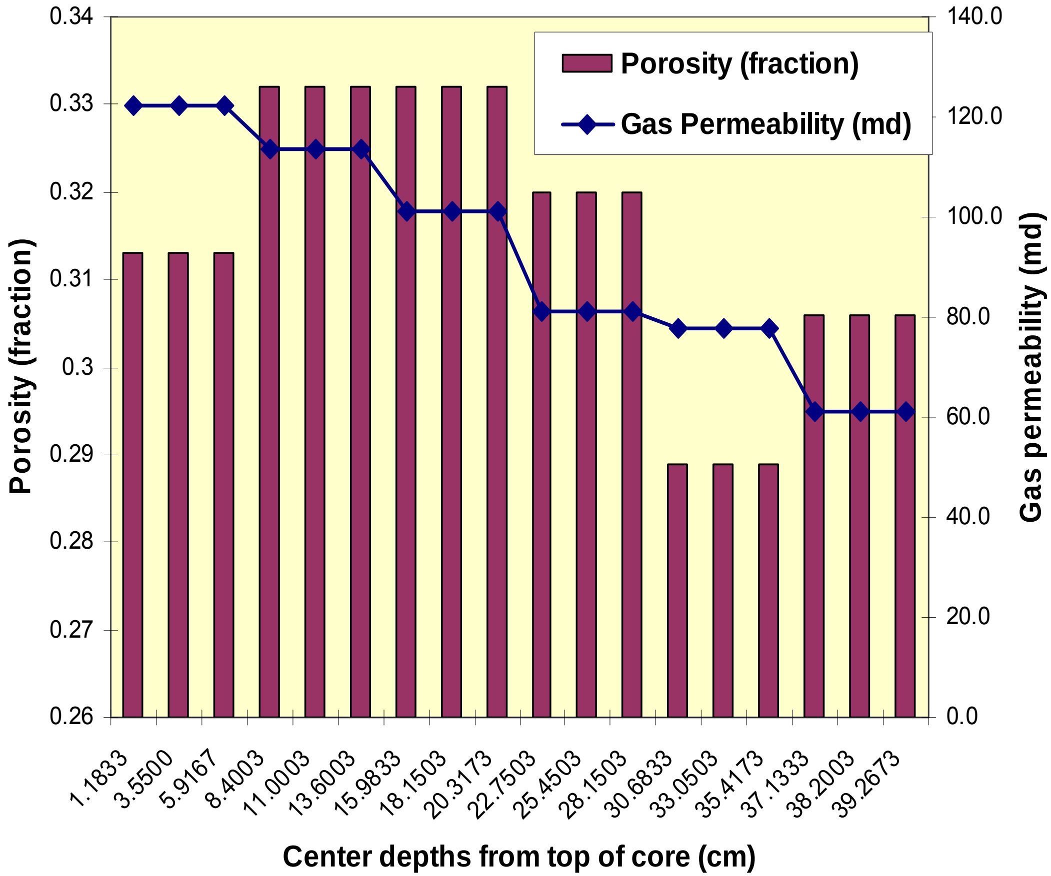
pore scale physics
wettabilty measurements
cryo ESEM

Modeling of mixed-wet core flooding experiments

- Improved model for saturation functions is established – ODD3P – in reservoir simulation software
- Numerical generated two-phase saturation functions can be established through the *e*Core technology
- Can Core flood modeling be done better?
- Old core flooding experiments with mixed wettability revisited:
  - Establishing "irreducible" water saturation
  - Water displacement
  - Gas displacement

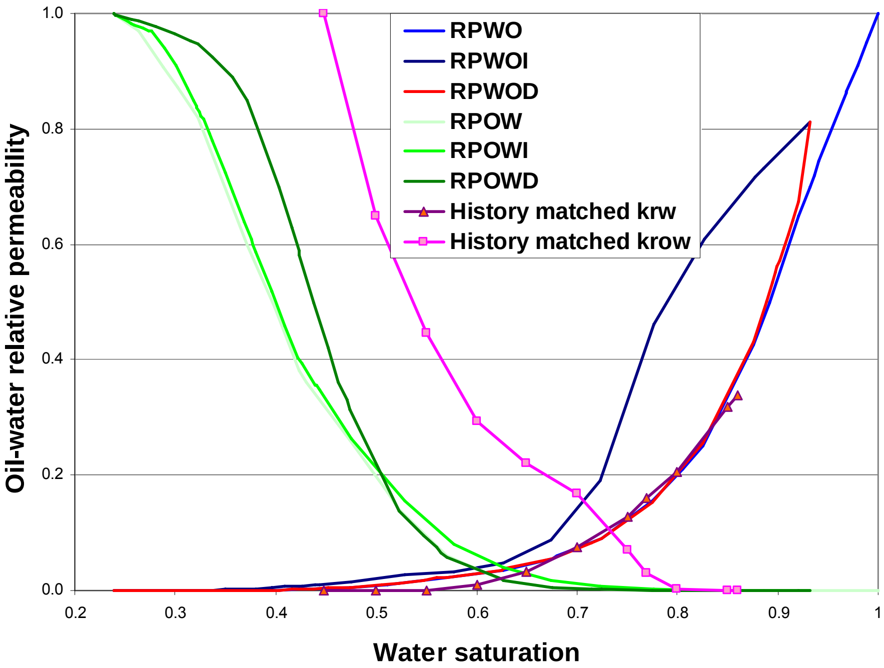
Displacement experiments
Composite core and numerical model

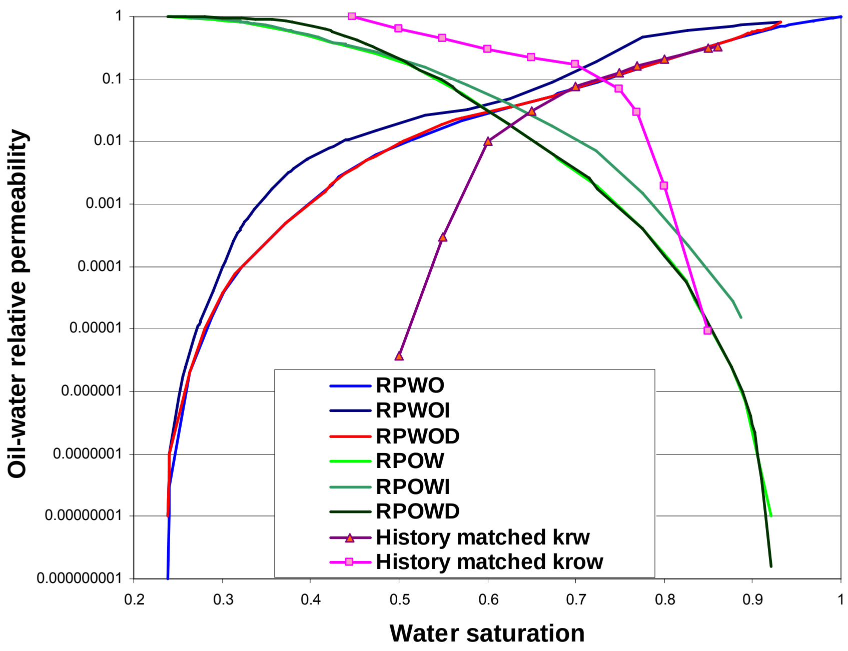
- Vertical composite core of six core plugs
- Three gridblocks representing each core
- Pore volume of 143.57 cm^3
- Two gridblocks were added to represent the end-pieces having zero capillary pressure
- Each end gridblock has a pore volume of 1 cm^3



Oil-water Relative permeability

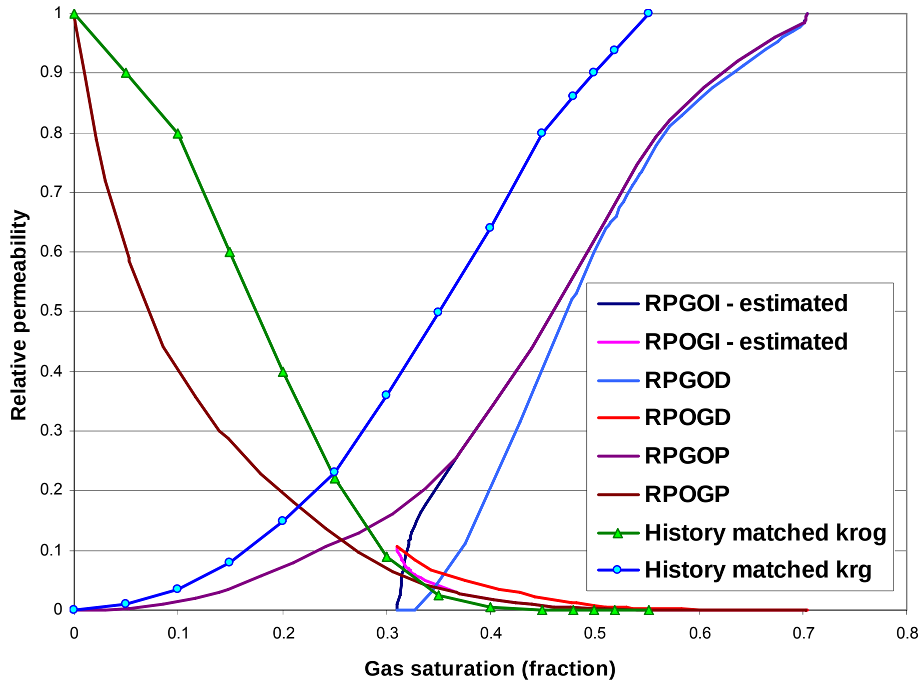
- Observe the crossing hysteresis relative permeability curves to oil from *e*Core
- Oil-water relative permeability is the same for all the cores
- S_{orw} is 6.8% and S_{wro} is 23.82%

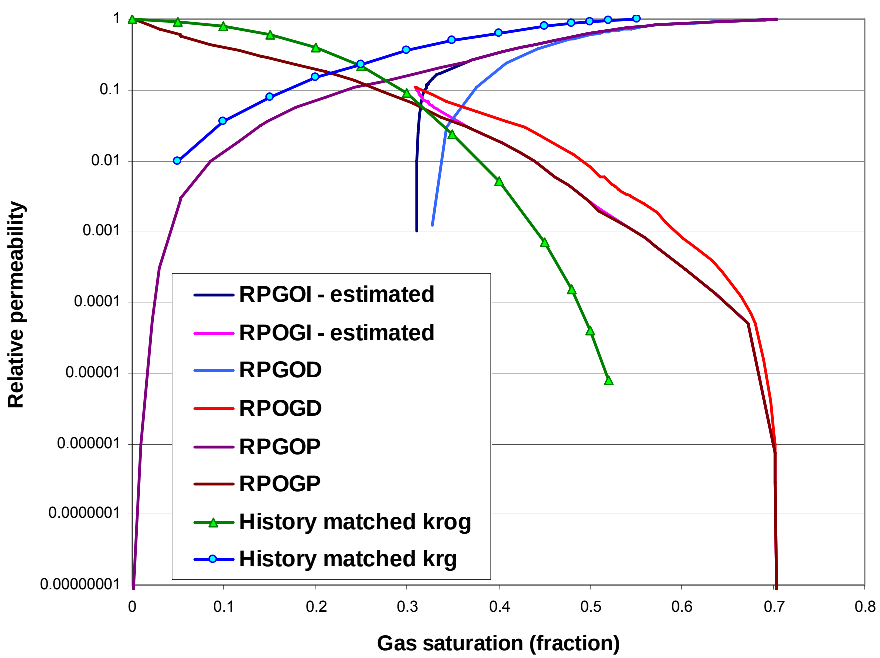




Gas-oil relative permeability

- Secondary drainage (network) curves have been estimated
- Note difference in estimated data through history matching
- The gas-oil relative permeability curves are the same for all the cores, and these are at S_{wro}
- S_{org} is 5.8% and S_{gro} is 31%, both at S_{wro} of 23.82%





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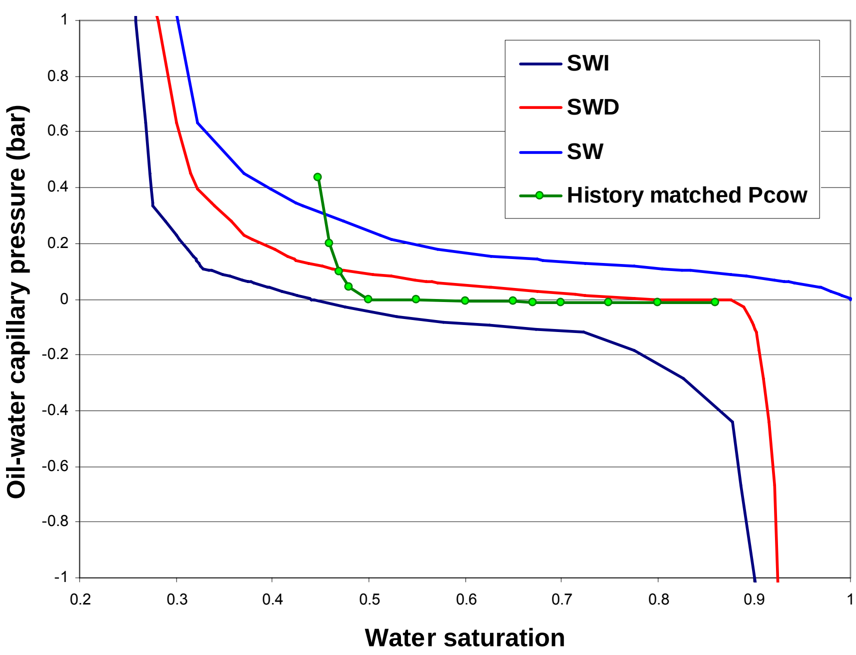
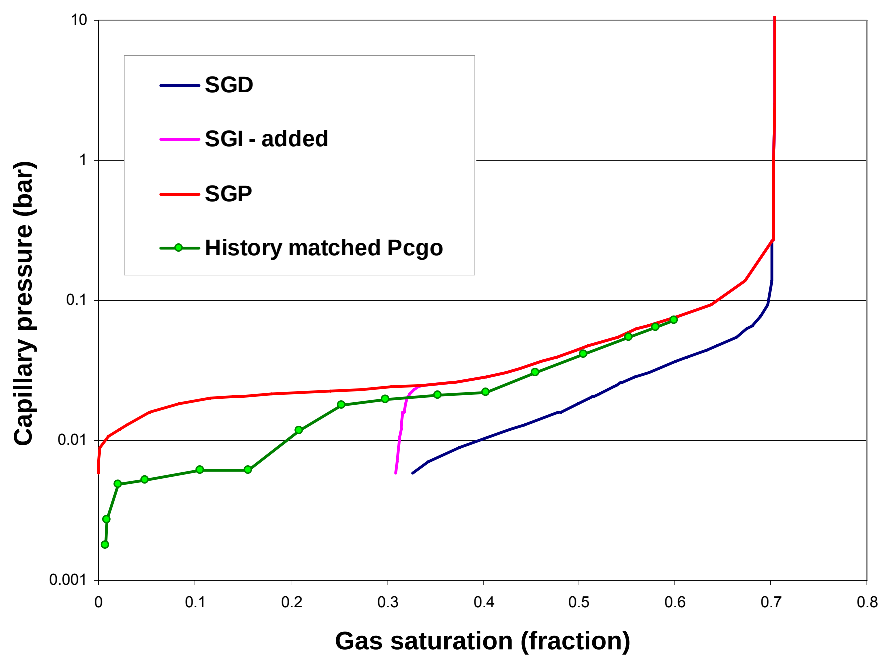
Capillary pressures

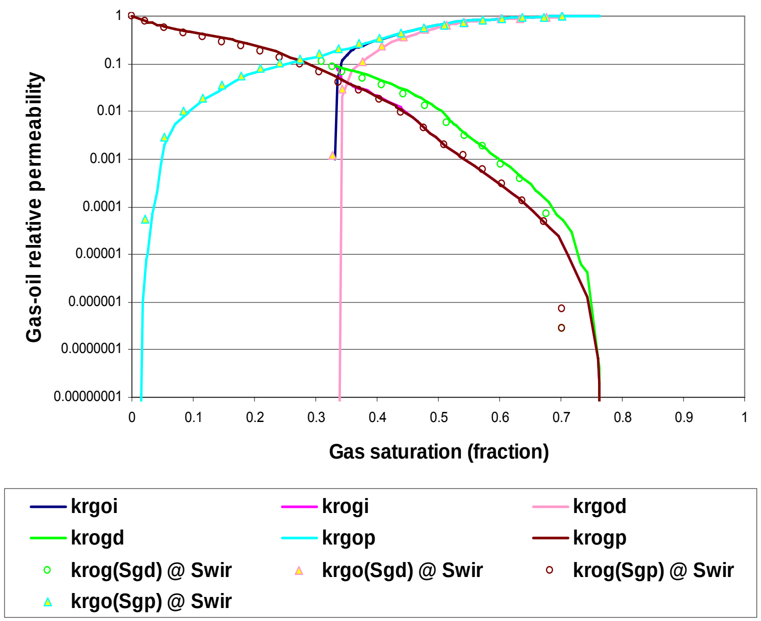
- The cores are assumed of fine grained sandstone and gas-oil data are at S_{wro}
- Capillary pressure curves are scaled according to Leverett J-function formulation from core to core. Curves for one core are illustrated here
- History matched data are significantly different

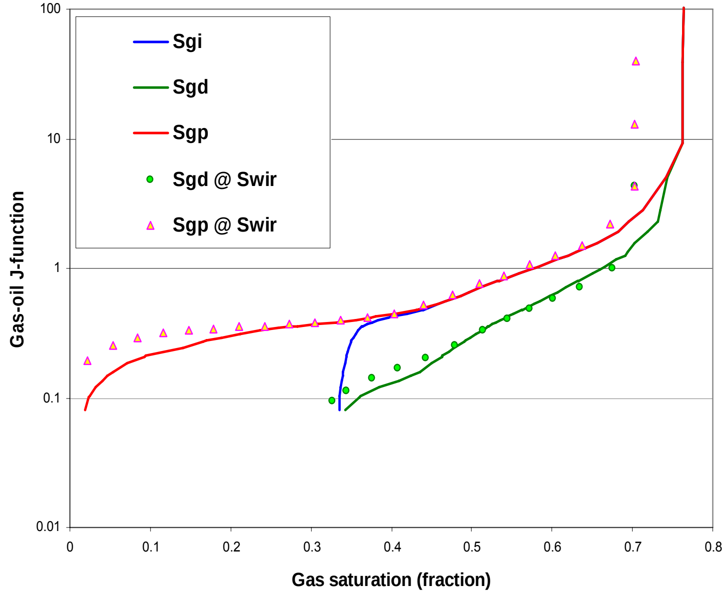




Comparing gas-oil saturation functions

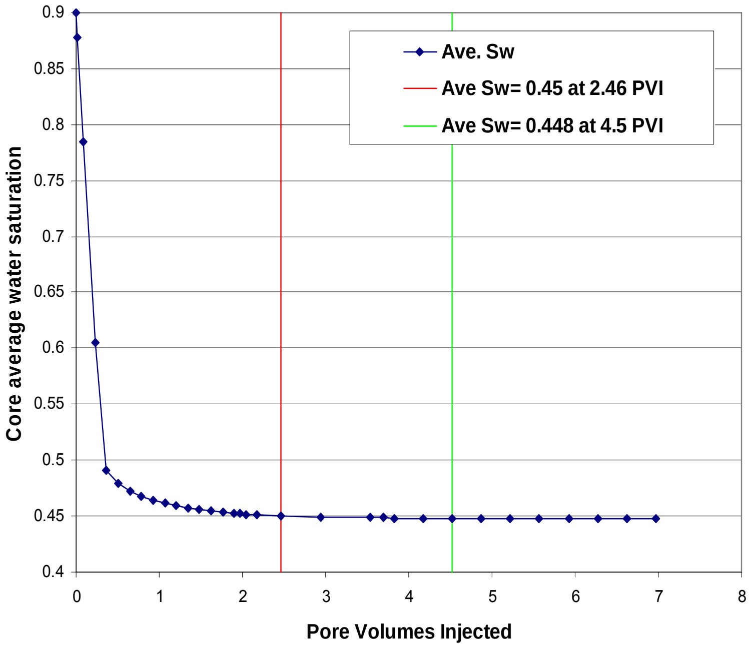
- The presence of irreducible water does not impact the relative permeability data, except near the end-point saturations.
- Maximum gas saturation is lower in the presence of water
- Slightly higher gas-oil J-function values are obtained at low gas saturation (<20%) and different near the maximum gas saturation.
- Residual gas saturation is slightly lower in the presence of water (0.8% points lower).

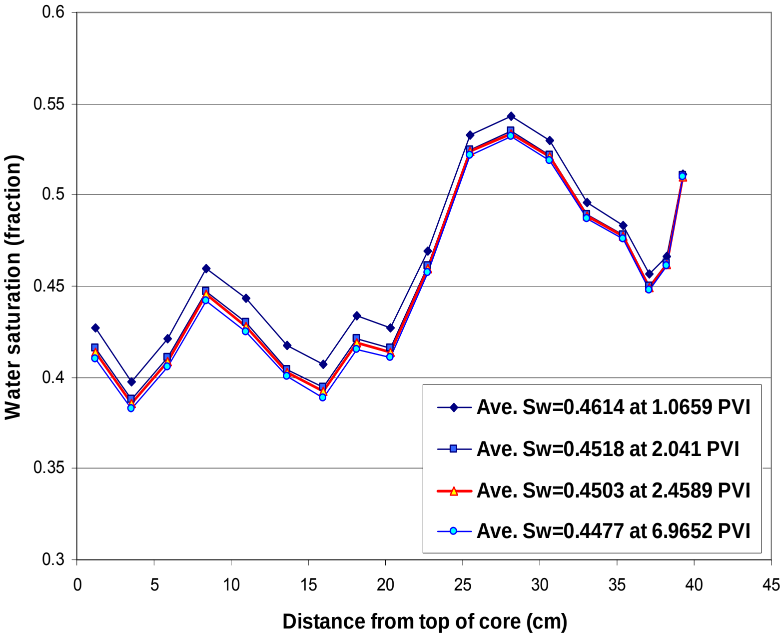




Primary Drainage

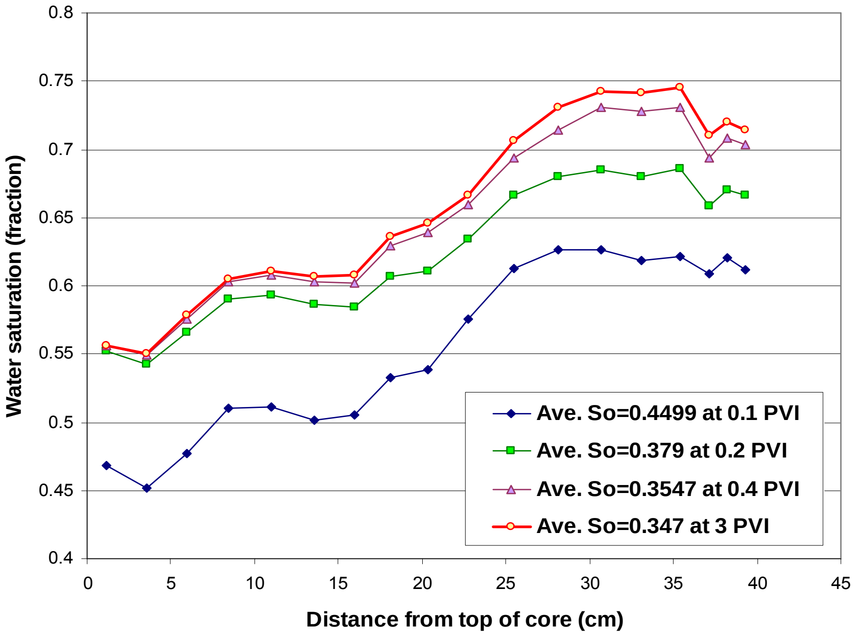
- Initial composite core water saturation was 45% and 44.8% for the water flood and gas flood experiment
- With direct use of network model data a match was achieved. No history matching or alterations performed!
- Initial water saturation of 45% and 44.8% corresponds to 2.5 and 4.5 pore volumes of oil injected

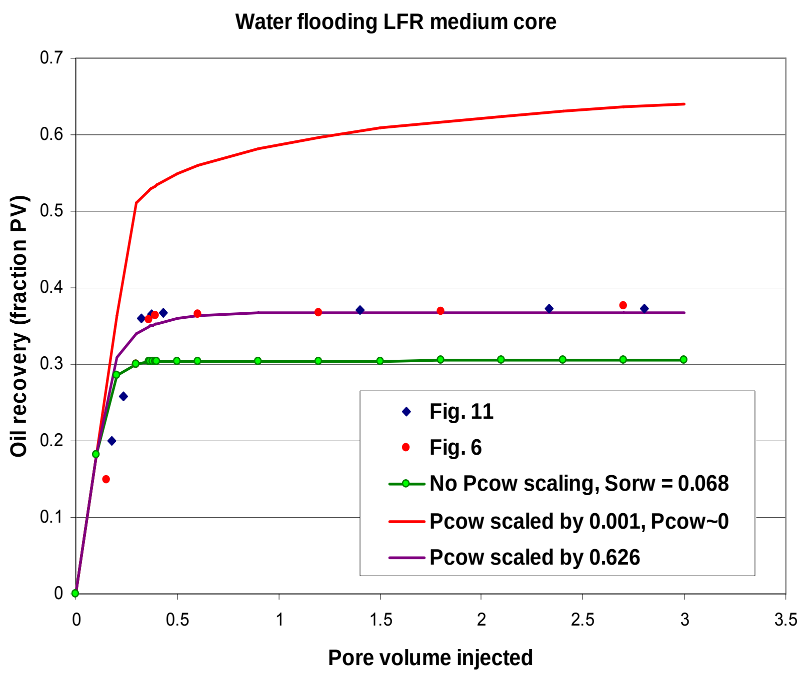




Water flooding

- Oil-water P_c-curve had to be modified/scaled by a factor 0.626
- Application of Leverett J-function may be questioned

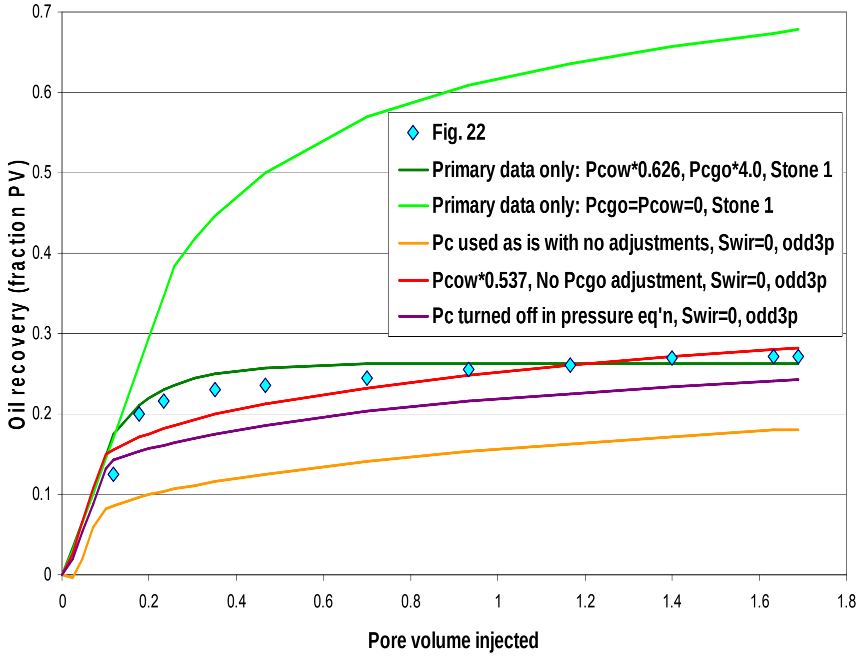




- The Amott wettability index of 0.1 may not be representative
- Good match of recovery curve was achieved with minor adjustments
- Zero capillary pressure will result in optimistic recovery

Gas Flooding

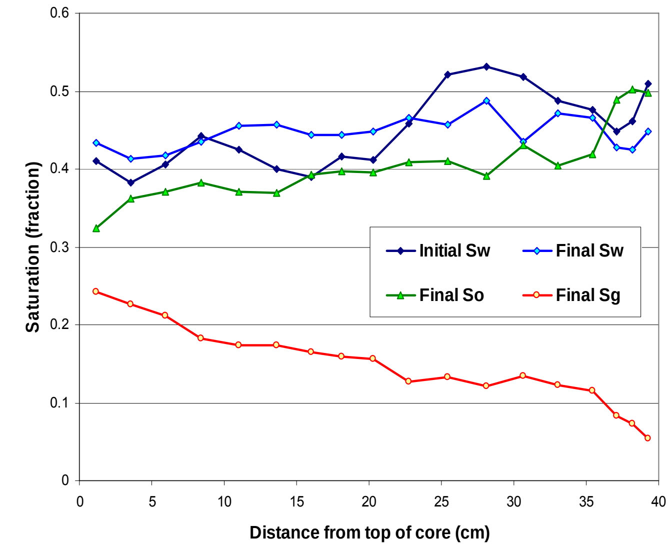
- Simulated scenarios used Stone's first model and ODD3P model
  - –Only primary data applied in Stone's first model (no hysteresis)
  - –All *e*Core data applied using ODD3P model
- Stone's first model "matched" the oil recovery, but the input gas-oil capillary pressure had to be adjusted by a factor 4!

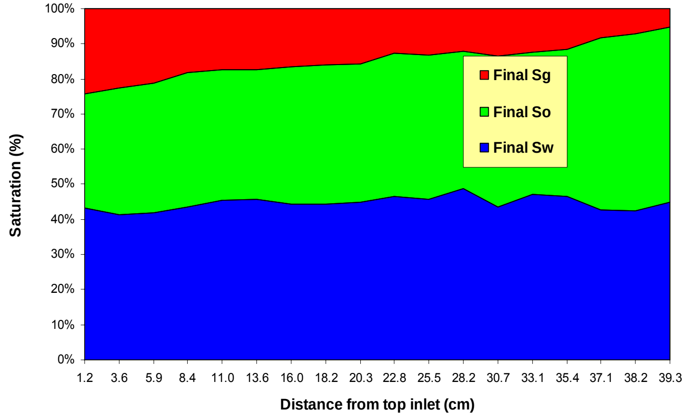


- Omitting capillary pressure in Stone's first model results in optimistic recovery
- Too low oil recovery with *e*Core data and ODD3P model with no adjustments
- Reducing oil-water capillary pressure gave more correct oil recovery level and adjusting gas-oil capillary pressure had little impact
- A fair match was achieved with ODD3P when the capillary pressure was turned off in the solution of the pressure equation. This example show significant CPU time improvement

Gas Flooding cont.

- The simulated final gas saturation show large gradient with the composite core
- The initial water saturation is redistributed when gas enters the core with less end effects
- The gas displaces mainly the oil volume and not the water volume during the gas displacement.
- The gas injection process does not leave primary curve due to breakthrough (short-circuiting flow) and high end-point hysteresis saturation (S_{rg}>30%)
- The laboratory boundary conditions seem to have little impact on the saturation end-effects (i.e. large gradients near the outlet) due to the wetting conditions





Concluding remarks

- Reservoir simulation technology improvements by StatoilHydro innovation
- StatoilHydro is approaching predictive capability when modeling core displacement experiments
- Work is ongoing to validate *e*Core technology for modeling core flooding experiments using ODD3P
- Further research still required
  - Need more data containing multi-phase flow
    - Lack good experimental data with different wettability, miscibility, hysteresis, etc.
  - Improve the modeling capability and understanding the application of experimental data
    - Better relationships between the parameters for multi-phase flow

The End

Thank you for listening

Questions?