公开课第12课

CO_2提高采收率数值模拟进展

GEM

Advances in CO_2 EOR Reservoir Modelling

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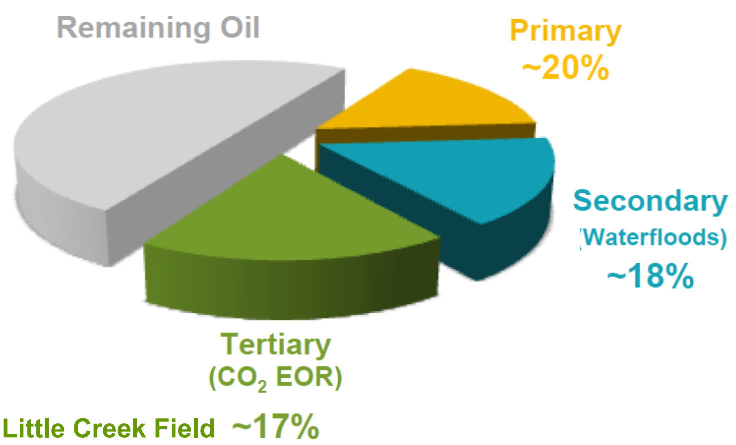
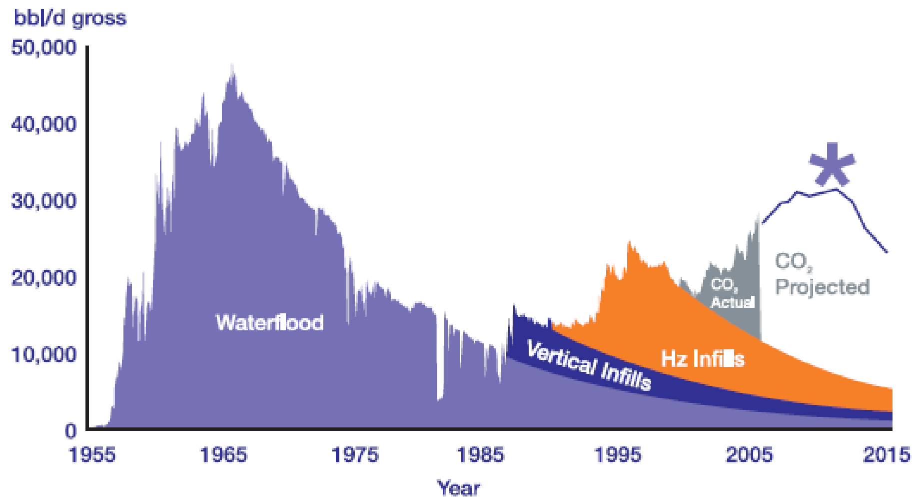
Agenda

- Introduction to EOR Processes
- Design Steps of CO_2 EOR
- Mechanism Important to Process
- Advances in Hybrid EOR Processes
- Practical Workflow & Case Studies
- Conclusions

Why EOR Processes?

Oil recoveries from primary and secondary recovery phases are generally in the range of 20–40% of OOIP



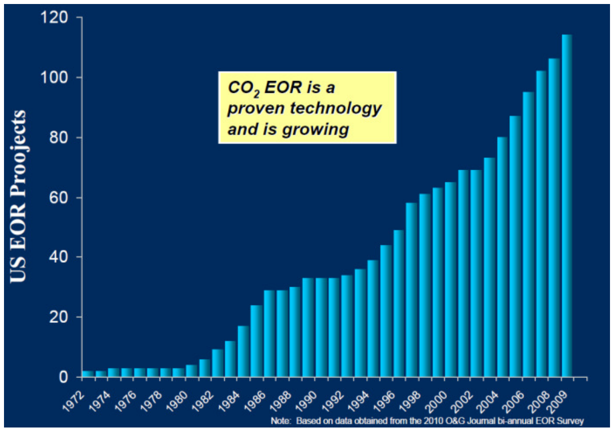


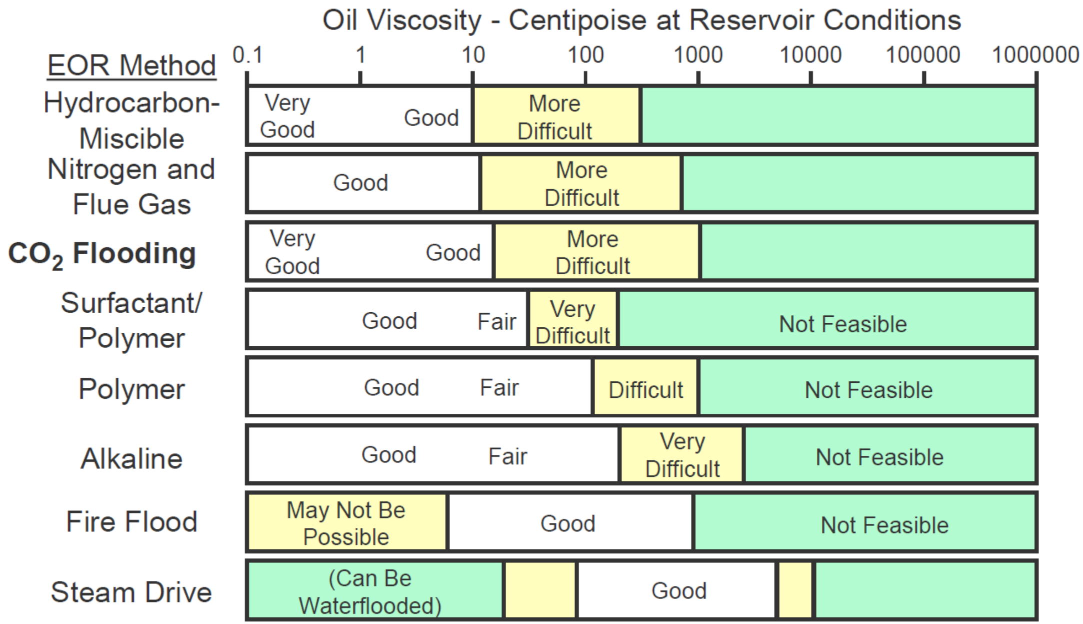
*Weyburn Project, Canada

Why CO_2 EOR?

Two major advantages:

- Additional oil recovery
- CO_2 storage to reduce emissions of CO_2





Source: Larry Lake

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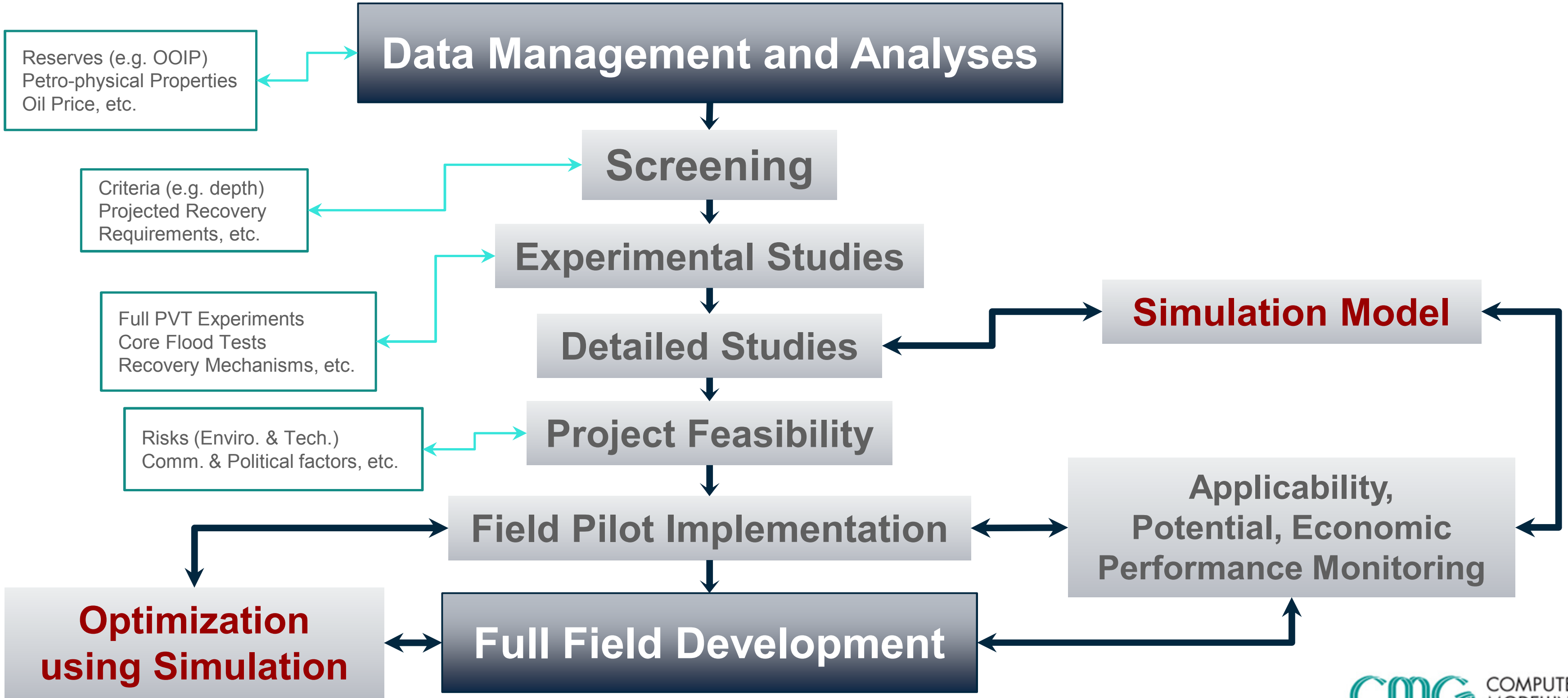
Miscible or Immiscible CO_2 EOR?

- Proven to be technically feasible in miscible and immiscible modes
- Among 123 CO_2-EOR projects in the United States, 114 are miscible projects *(koottungal, 2012; kuuskraa, 2012)*
- Mainly on light to ultra-light oils (>28°API) with a viscosity of less than 3 centipoise

Design Steps of CO_2 EOR



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What Does Reservoir Modelling Aim at?

Better Understanding of Reservoir Performance

Steps to Make a Representative Model?

STEP 1: Reliable data Input
- Reservoir Parameters, PVT, etc.

STEP 2: History Matching
- Production and pressure history data

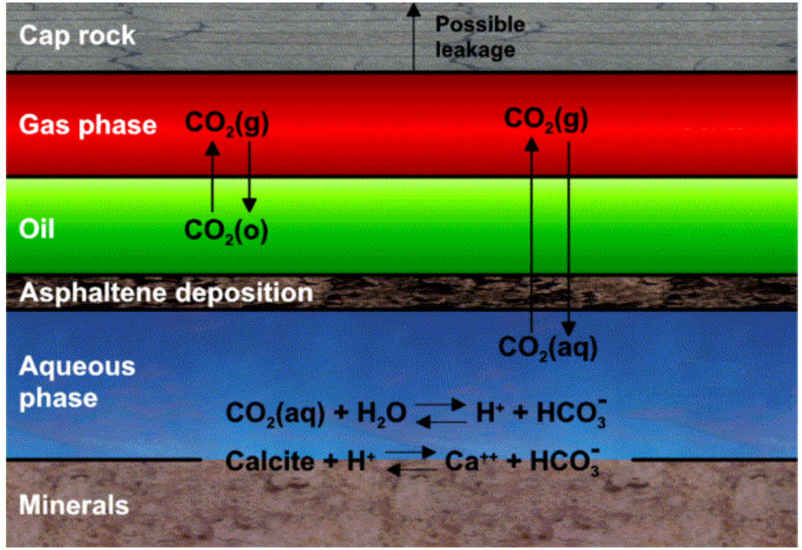
STEP 3: Forecast
- Different scenarios, optimum design, etc.

Most Important Step
Needs understanding of physics and important mechanisms

Reliable and Capable Modelling Tool

CO_2 EOR Mechanisms

- PVT, solubility, and swelling
- Miscibility mechanisms
- Asphaltene deposition
- Wettability Alteration
- Hysteresis
- IFT Effects
- Diffusion and Dispersion



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Additional Process Mechanisms

- Matrix dissolution from CO_2 injection
- Aqueous chemical equilibrium reactions
- Ion-exchange
- Mineralization: dissolution and precipitation
- Thermal effects
- CO_2 leakage through caprock

What to Use?

Advanced general equation-of-state compositional simulator

Simulates compositional effects of reservoir fluid during primary and enhanced oil recovery processes

Phase behaviour and reservoir fluid property program for PVT modelling and data matching

For modelling of:

- Gas condensates
- Tight/shale gas
- CO_2 EOR
- WAG
- Chemical EOR
- CO_2 Sequestration
- LSW flooding
- Polymer Flooding
- ASP flooding
- …

What to Use?

CMOST

Sensitivity Analysis

- Better understanding of a simulation model
- Identify important parameters

History Matching

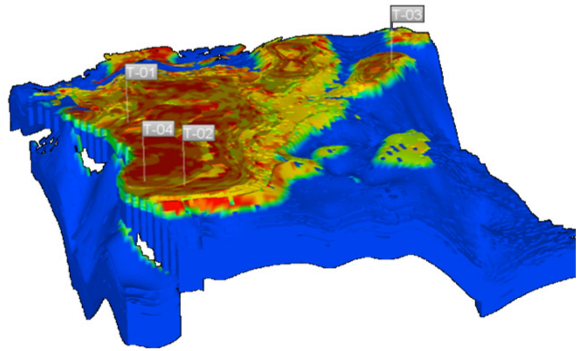
- Calibrate simulation model with field data
- Obtain multiple history-matched models

Optimization

- Improve NPV, Recovery, …
- Reduce cost

Uncertainty Analysis

- Quantify uncertainty
- Understand and reduce risk



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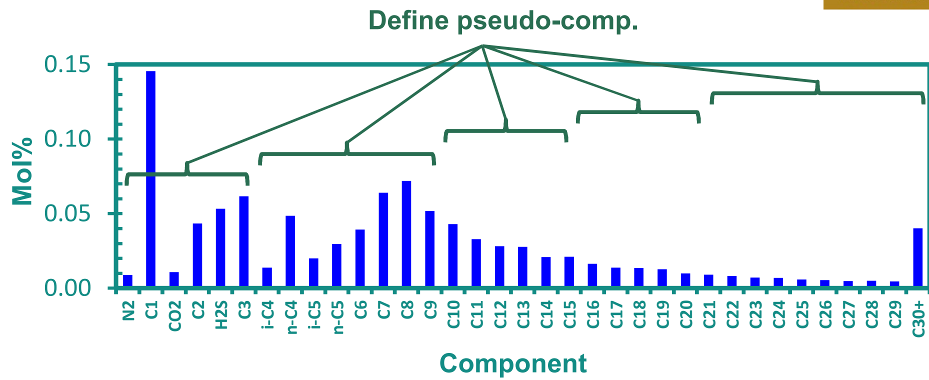
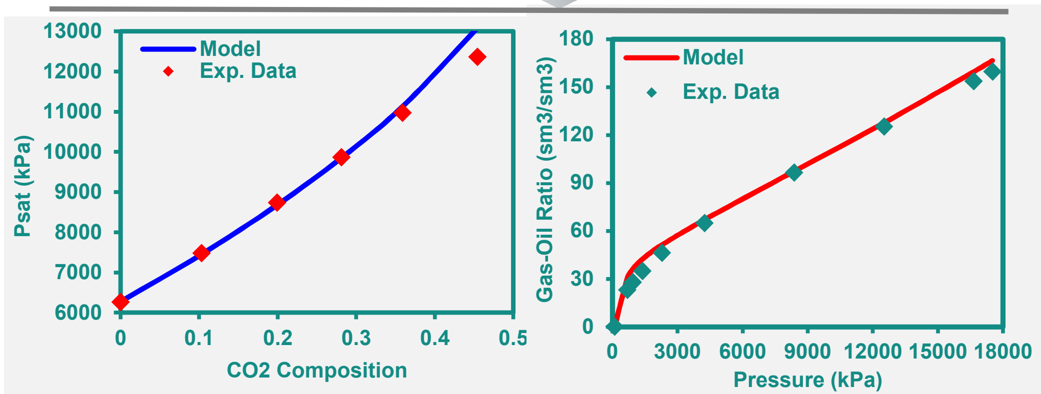
PVT

- **Fluid Characterization**
  - Compositional Analysis
  - Recombination
- **Lab Data Matching**

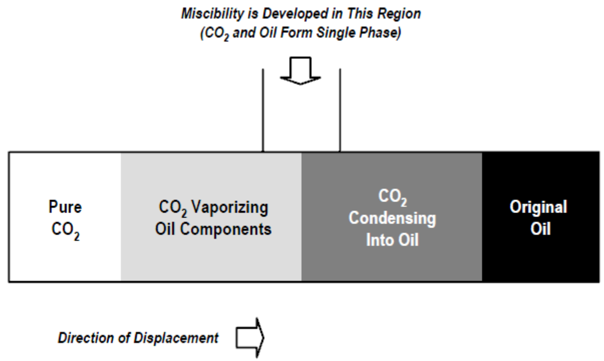
  → *P*, *T*, and composition variation
  - CCE
  - Differential liberation
  - Separator test
  - Swelling test

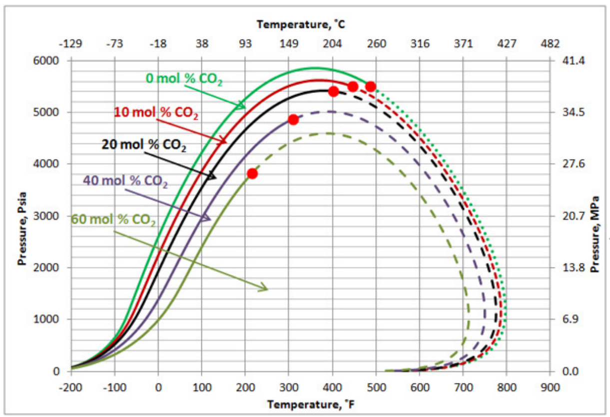


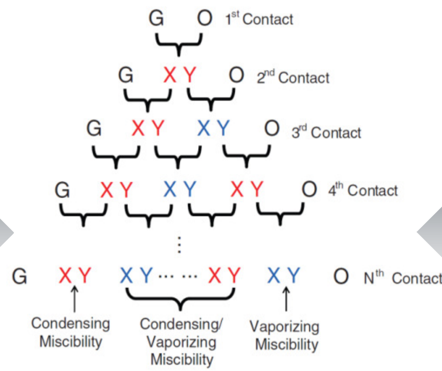


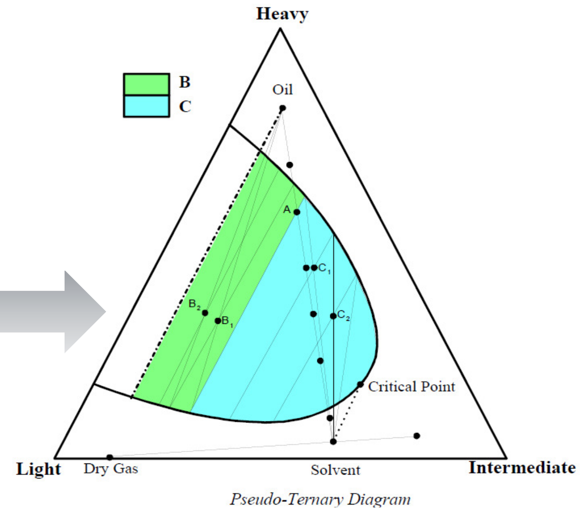
Miscibility Mechanisms

- Vaporizing, condensing, combined
- MMP and MME determination
- Methods
  - Cell to Cell
  - Multiple Mixing Cell
  - Semi-Analytical





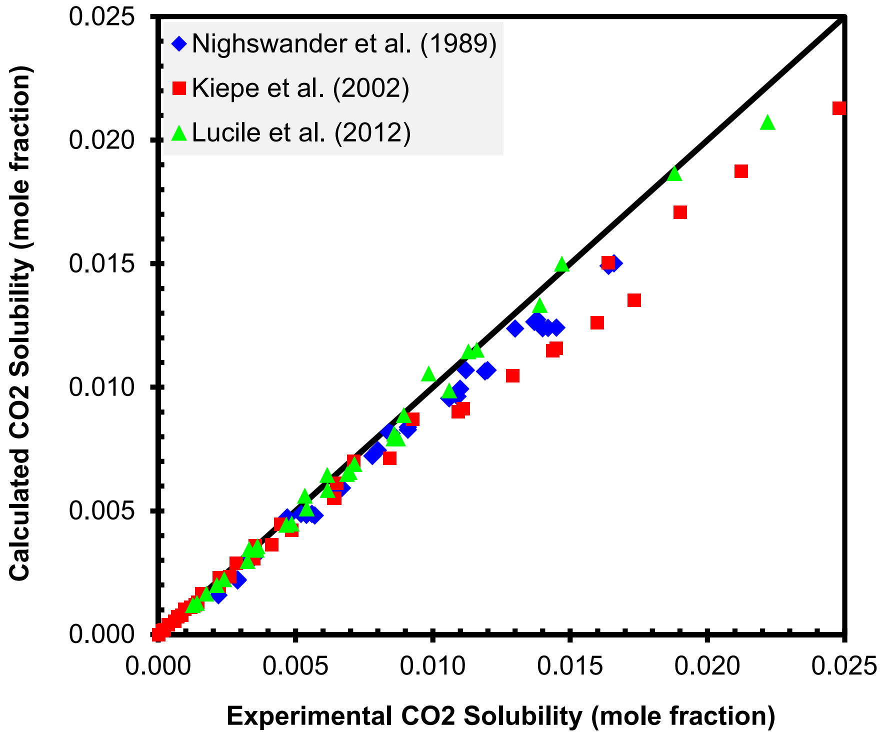




Solubility in Water

- Direct Henry's Constant Input

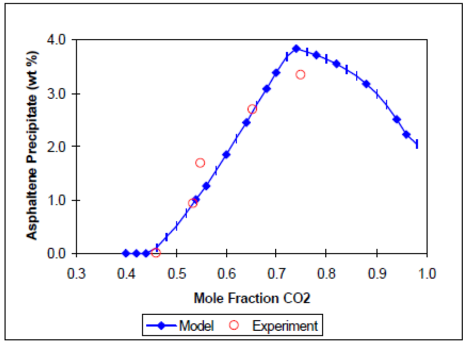
- Correlations
  - Harvey's Method
  - Li-Nghiem's Method
  - Account for Salinity

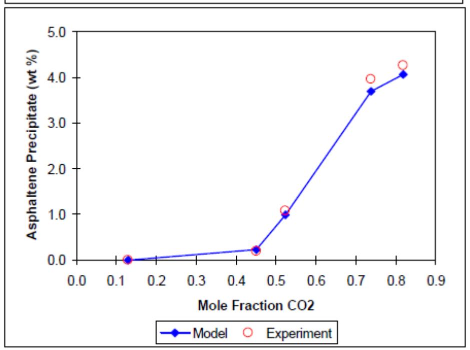


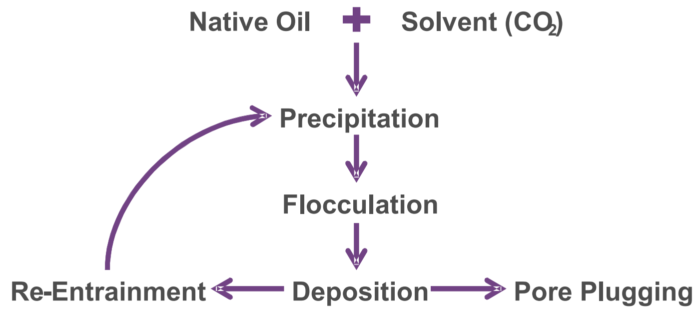
Asphaltene Precipitation

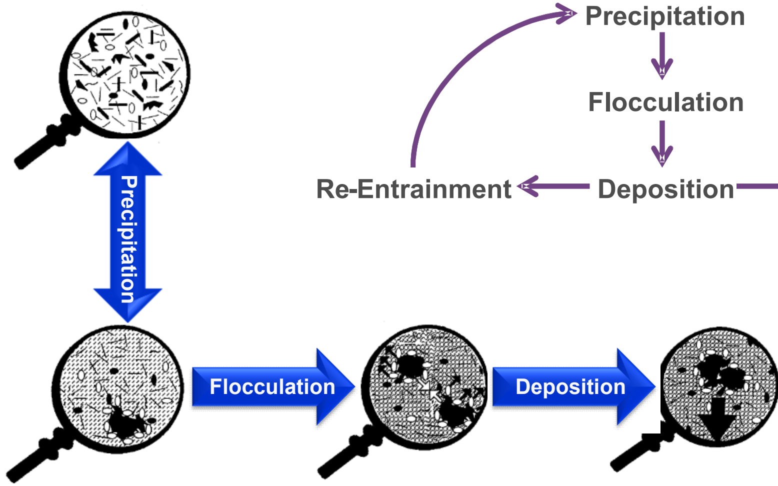
Change in *P*, *T*, or Composition

- Asphaltene/Wax Modelling





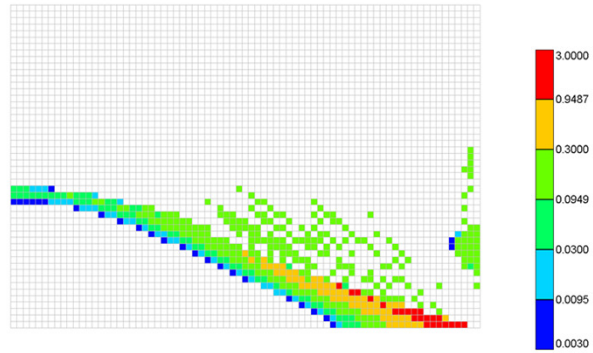




Flocculation and Deposition

Plugging and Permeability Impairment

- Flocculation
  - Aggregation into larger particles
  - Suspended component



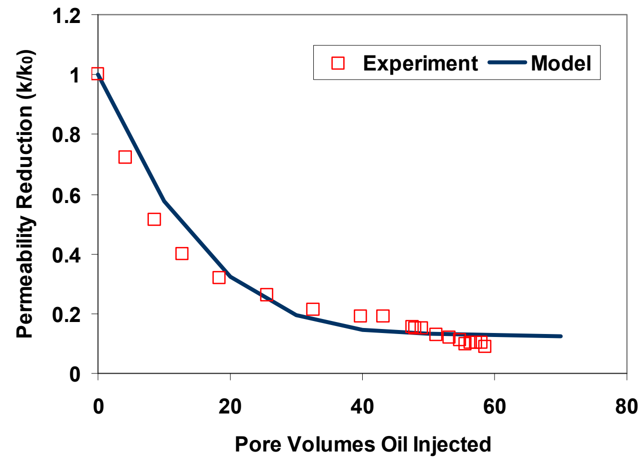
- Deposition
  - Surface deposition, plugging deposition and re-entrainment
  - Non-equilibrium Blockage

Blockage

- Resistance Factor Calculation
  - Power Law Model
  - Kozeny-Carman Equation
  - Solid Adsorption Model

- Permeability is divided by the resistance factor while calculating the phase transmissibilities

$$k = k_0 / rf$$



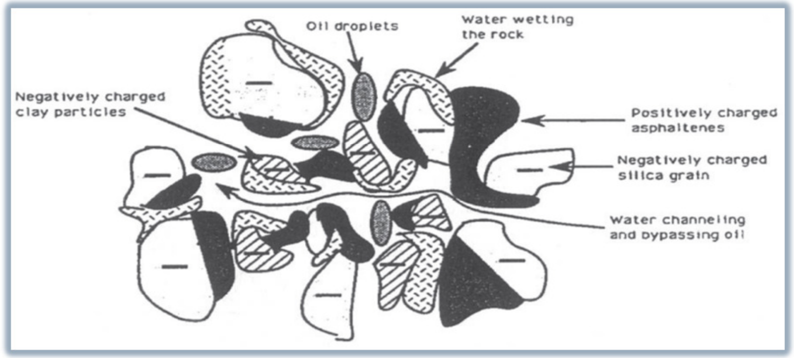
Wettability Alteration

- Wettability alteration
  - Asphaltene adsorption
  - Geochemical interaction/ion exchange

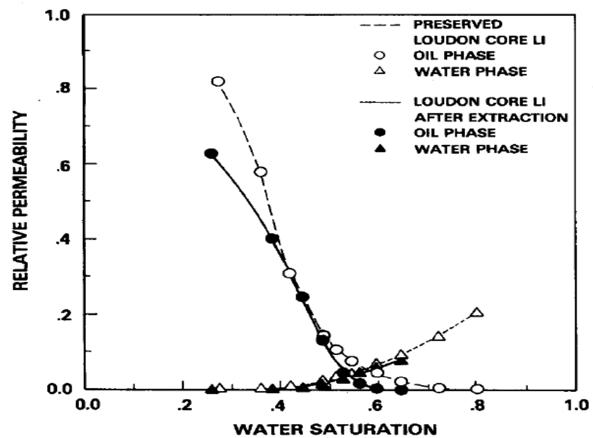
- Capillary pressure and relative permeability curves change

  * KRINTRP

  * INTCOMP



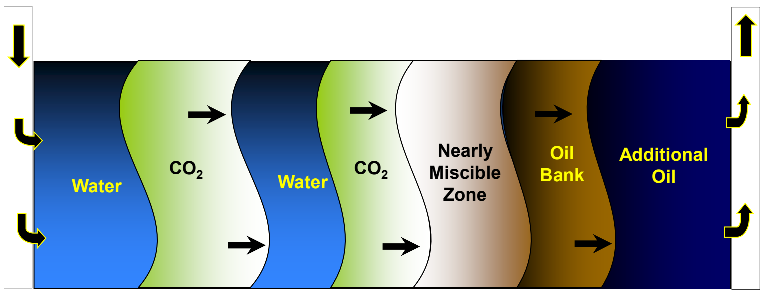
Leontaritis et al. 1994, SPE 23810.

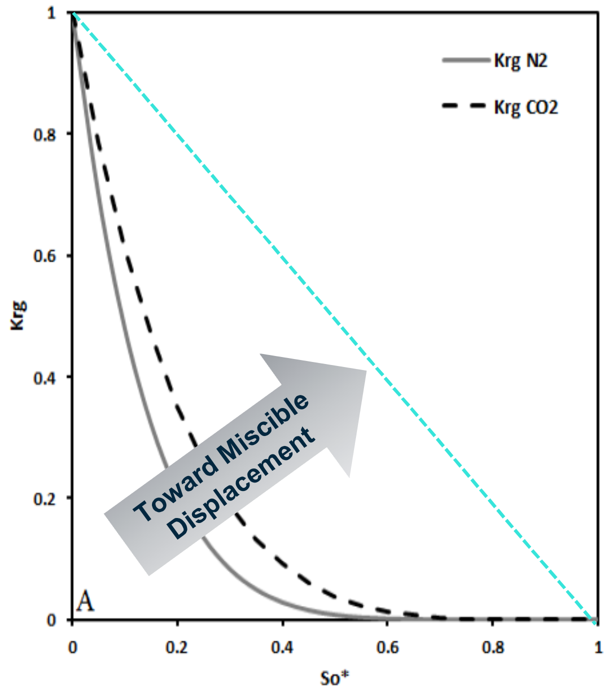


Wang 1988, SPE 37232

IFT Effect

- Relative permeability as a function of IFT
- At higher IFT, typical relative permeability curves
- Straight line relative permeabilities as the IFT is lowered





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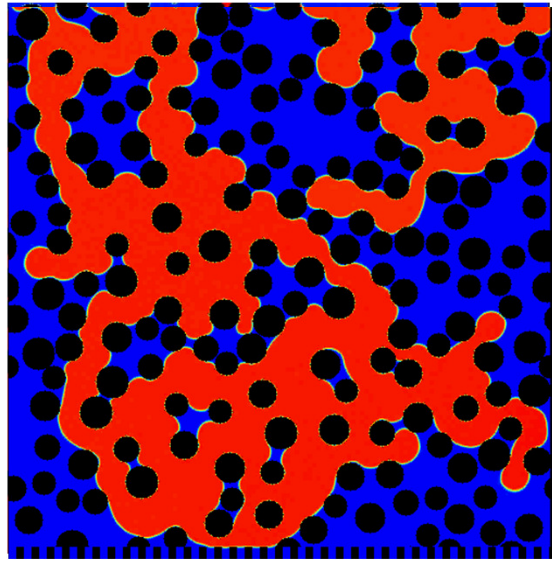
Hysteresis

A fluid (e.g. gas) moves into a pore:

1) Displaces fluid in pore (called drainage)

2) Sometimes displaced fluid moves back into the pore (called imbibition)

3) A shift in the Relative Permeability during this can trap some of the gas in the pore, making it immobile



Videos Courtesy Laboratório de Meios Porosos e Propriedades Termofísicas

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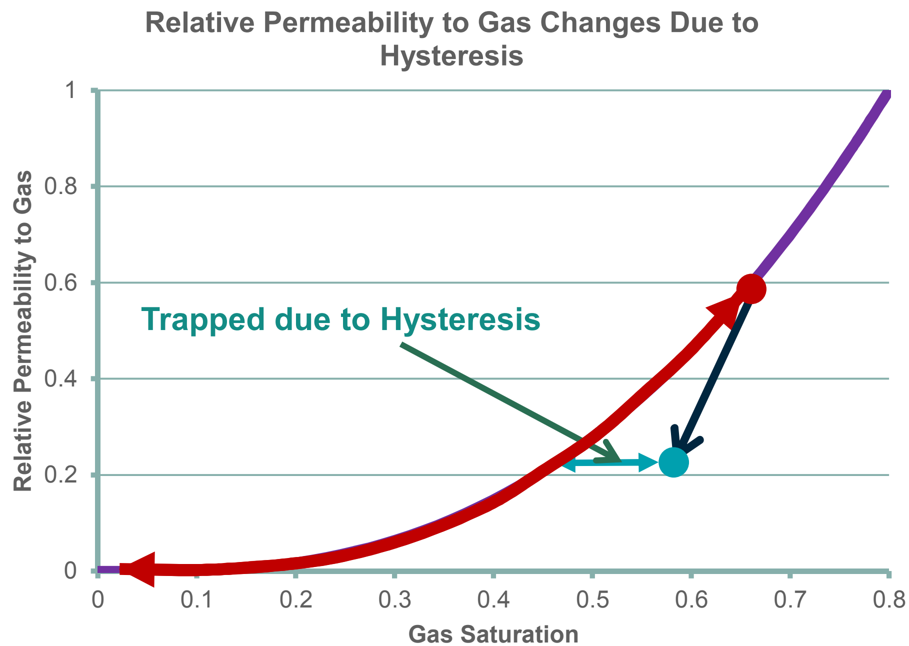

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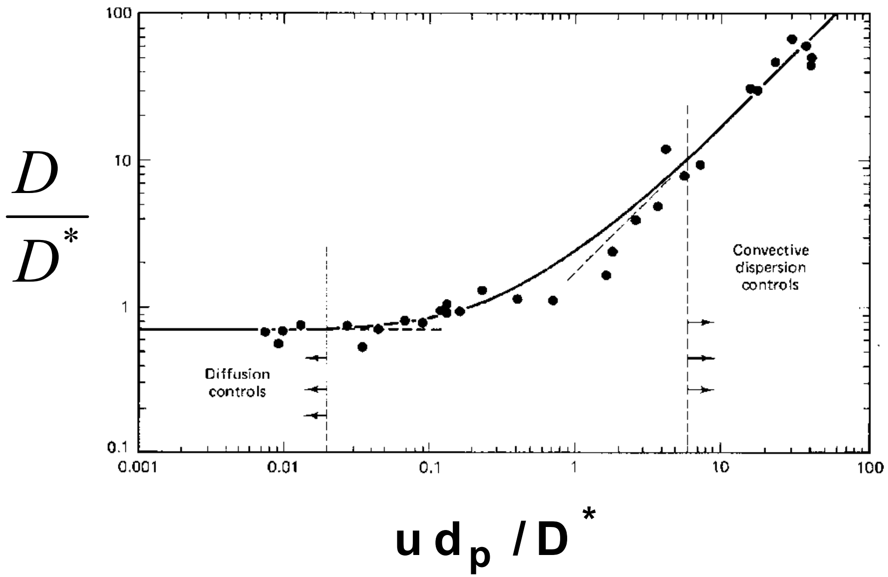
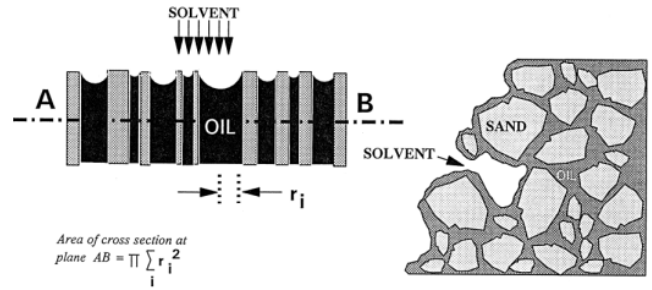
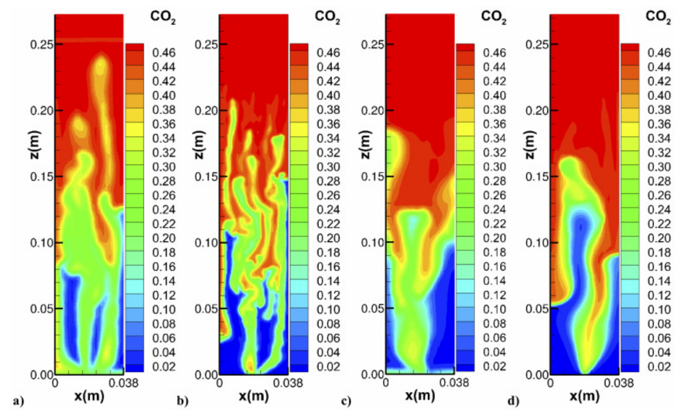
Diffusion and Dispersion







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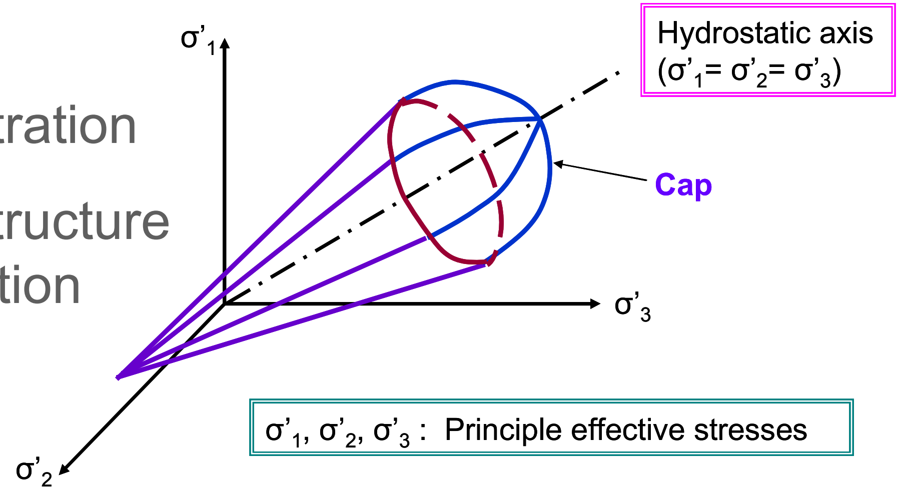
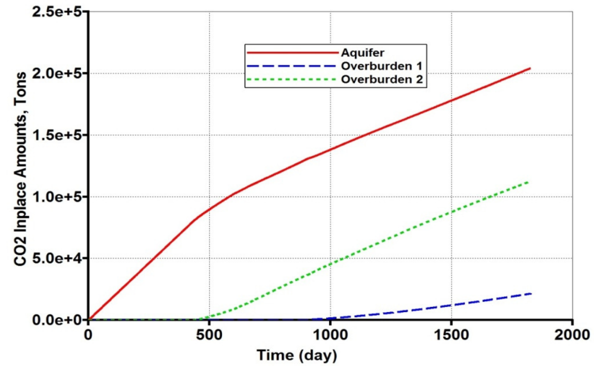
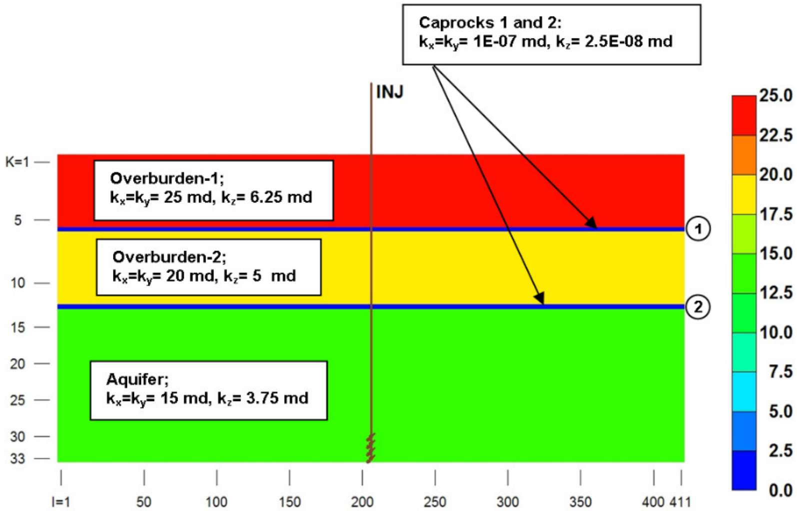
Geomechanics

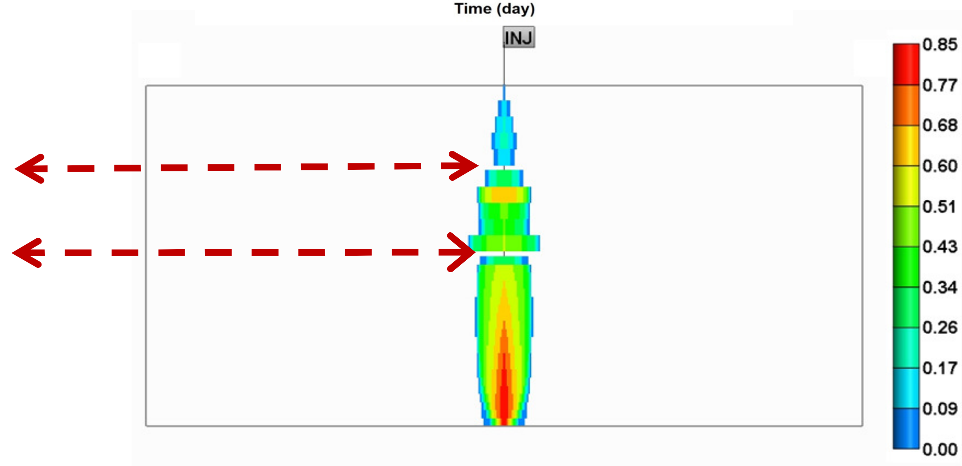
- Caprock integrity due to stress/strain relationships
- Different constitutive models
- Applications:
  - Risk assessment in sequestration
  - Deformation of geological structure due to fluid withdrawal/injection
  - Geomechanical effects on coal-seams
  - …



Geomechanics







Perkins and Johnston 1963

Advances in Hybrid EOR Processes

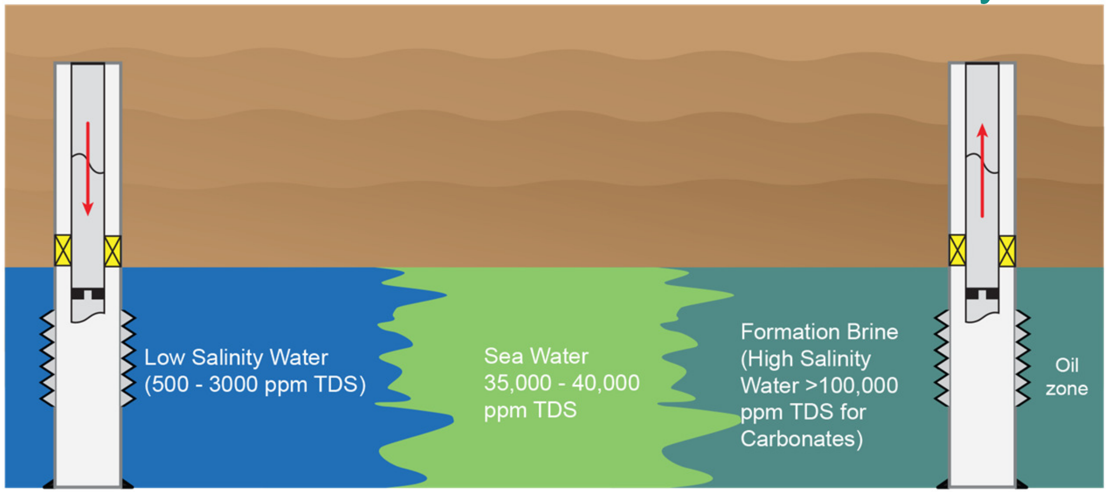
LSWI, Foam, etc.

CO_2 + Low Salinity Water Flooding

LSW is attractive because:

- Operationally identical to conventional waterflooding
- No requirements for expensive chemicals
- Possible significant increase in recovery

LSW works in oil-wet reservoirs with clay



Main mechanism: wettability change from oil-wet to water-wet

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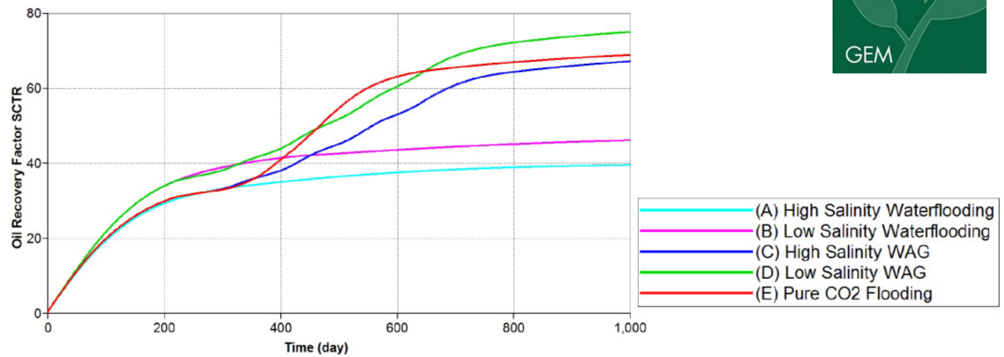
CO_2 LSWAG

CO_2 WAG

- CO_2 Miscibility
- Mobility Control (WAG)
- High Recovery Factor
- *Delayed Production Problem*

LSWI

- Wettability Alteration
- Higher Recovery w.r.t HSWI
- Lower Chemical Cost
- Environmental Impact
- Field Implementation
- *Lower Recovery w.r.t Miscible Floods*



CO_2 LSWAG

- Synergy of Mechanisms
- CO_2 Miscibility
- Mobility Control
- Wettability Alteration
- Geochemical Reaction with Inj CO_2
- Ion Exchange
- Dissolution of Carbonate Minerals
- *Higher Recovery w.r.t HSWI, LSWI, CO_2 HSWAG, and pure CO_2*
- *No Challenge of late Production*

GEM

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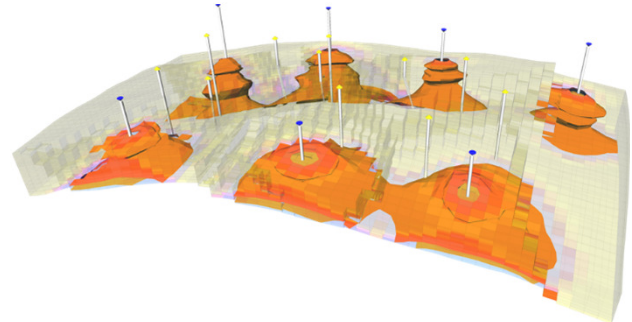
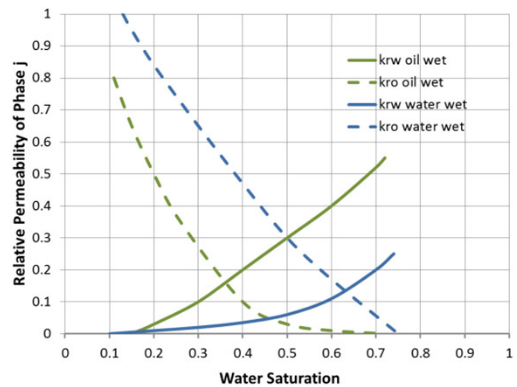
CO_2 LSWAG in GEM

- EOS compositional simulator
- Full geochemistry model
  - Aqueous reactions
    E.g. CO2(aq) + H2O = (H+) + (HCO3-)
  - Ion exchange equilibria
    E.g. (Na+) + 0.5(Ca-X2) = 0.5(Ca++) + (Na-X)
  - Mineral dissolution/precipitation reactions
    E.g. Calcite + (H+) = (Ca++) + (HCO3-)
- Interpolation between oil-wet and water-wet relative permeability based on ion exchange
- Models temperature effects on low salinity





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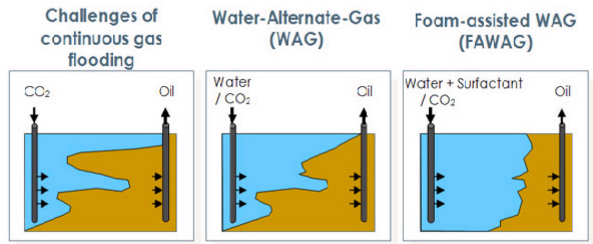
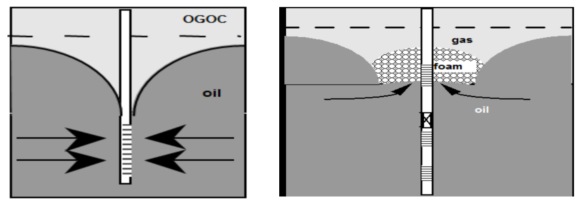
Foam Assisted CO_2 EOR

- **Gas Mobility Control**
  - Improve the sweep efficiency in by-passed oil zones
  - Foam is used to change the mobility of gas in the reservoir



- **Gas Shut-Off**
  - Foam around perforations reduce gas mobility and production in wells located near the gas oil contact



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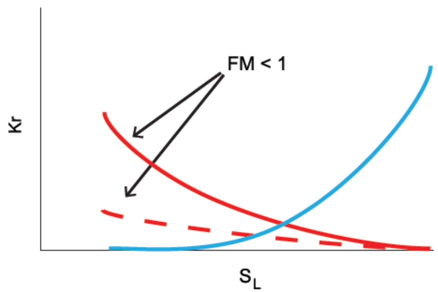
Advances in Foam Modelling

Modification of Relative Permeability

- Uses FM as interpolant
  - FM = 0 Strong Foam
  - FM = 1 No Foam
- Use FM as a multiplier to krg



Dependencies

- FMMOB: Foam Mobility
- F1: Surfactant Concentration
- F2: Oil Saturation
- F3 & F4: Capillary Number
- F5: Oil Composition
- F6: Salinity
- FDRY: Foam Dry Out

$$FM = \frac{1}{1 + FMMOB * F1 * F2 * F3 * F4 * F5 * F6 * FDRY}$$

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Practical Workflow

Practical Work Flow

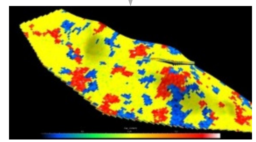
PVT Modelling

CCE, Diff Liberation Separator, Swelling Test, …

GEM 1D Model

Slim tube, Core-floods, …

Geological Modelling



Reservoir Simulation

Flow, Wettability Alteration, Miscibility, …

Sensitivity Analysis
History Matching
Optimization
Uncertainty Assessment

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Case Studies

Case Studies

Case 1: Field-scale inverted 5-spot pattern model

- Application of workflow

Case 2: Field scale model

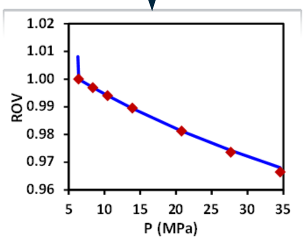
- Primary and Secondary Recovery HM
- WAG optimization
- Evaluation of Mechanisms

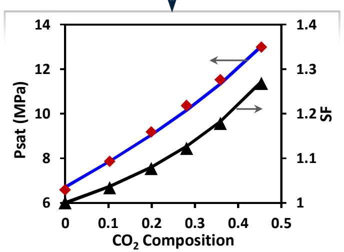
Case 1: Field-Scale 5-spot Model

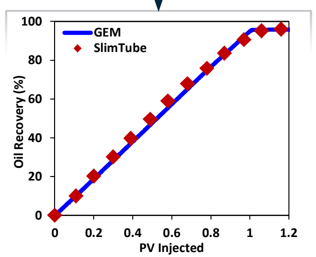
Data | Simulator | Goal

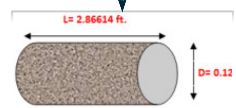
CCE, Diff Lib, Separator	Swelling test, Saturated μ , ρ	Slim Tube Test		Core Flood	
WINPROP	WINPROP	WINPROP	GEM	GEM	CMOST
Fluid Model	FCM, Oil/CO_2 Model	Thermodynamic Models (MCM)	1D Model Oil Recovery	1D Model WAG	SS & HM Rel Perm

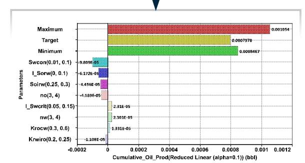
Check MMP
- Cell to Cell
- Multiple Mixing
- Semi-Analytical

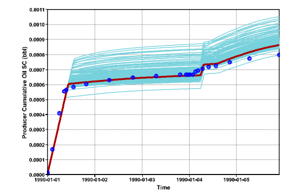




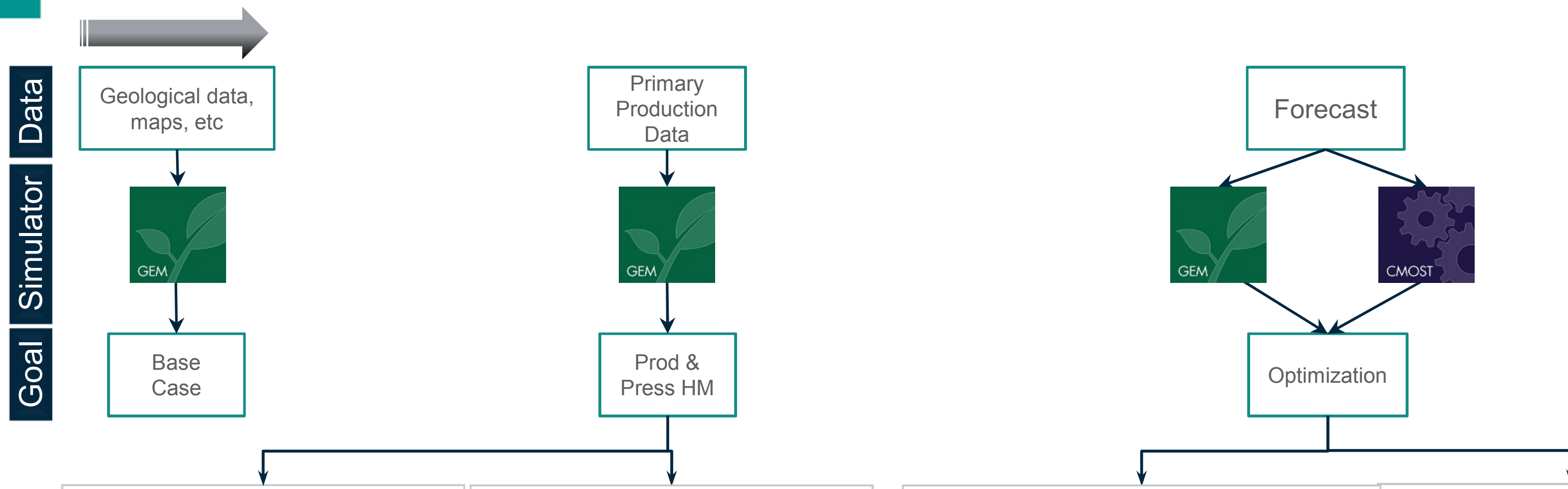


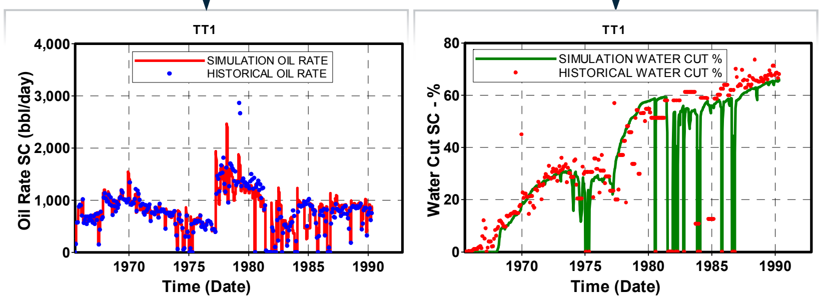


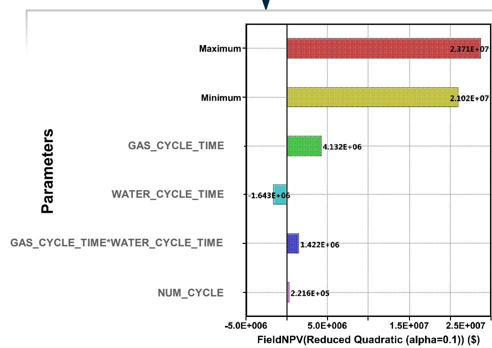


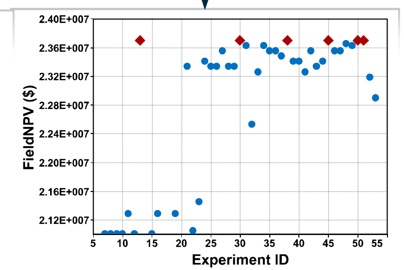


Case 1: Field-Scale 5-spot Model









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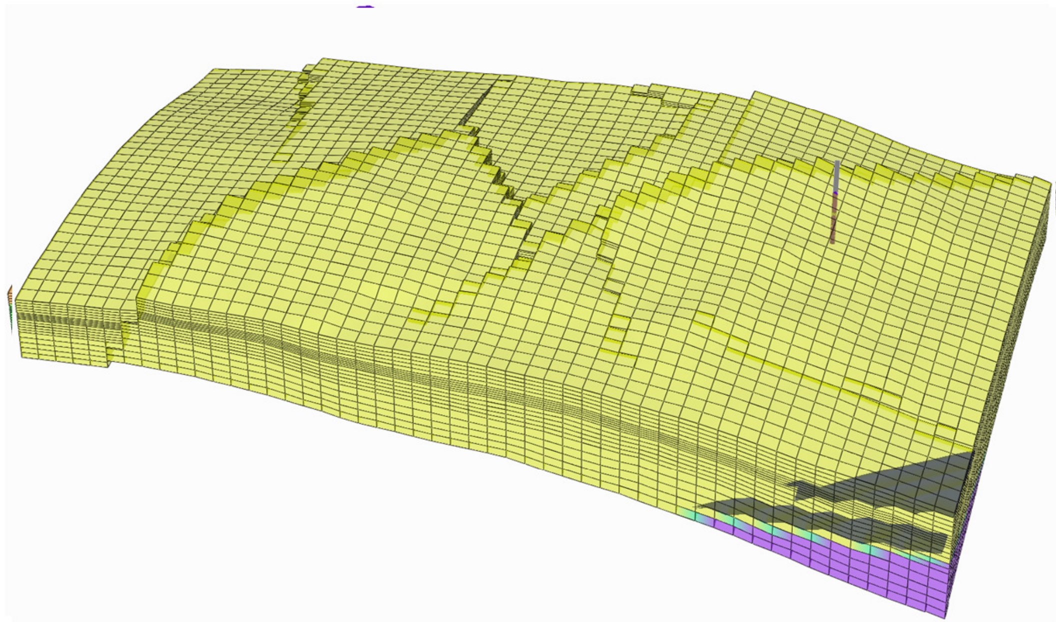
Case 2: Field Scale Model

Original Oil in Place (OOIP):
684.6 million barrels

- Start with 7 years of primary production (1983-1990)
- Followed by 18 years of water-flooding (1990-2008)
- Water-flooding followed by CO_2 WAG process from 2008-2035



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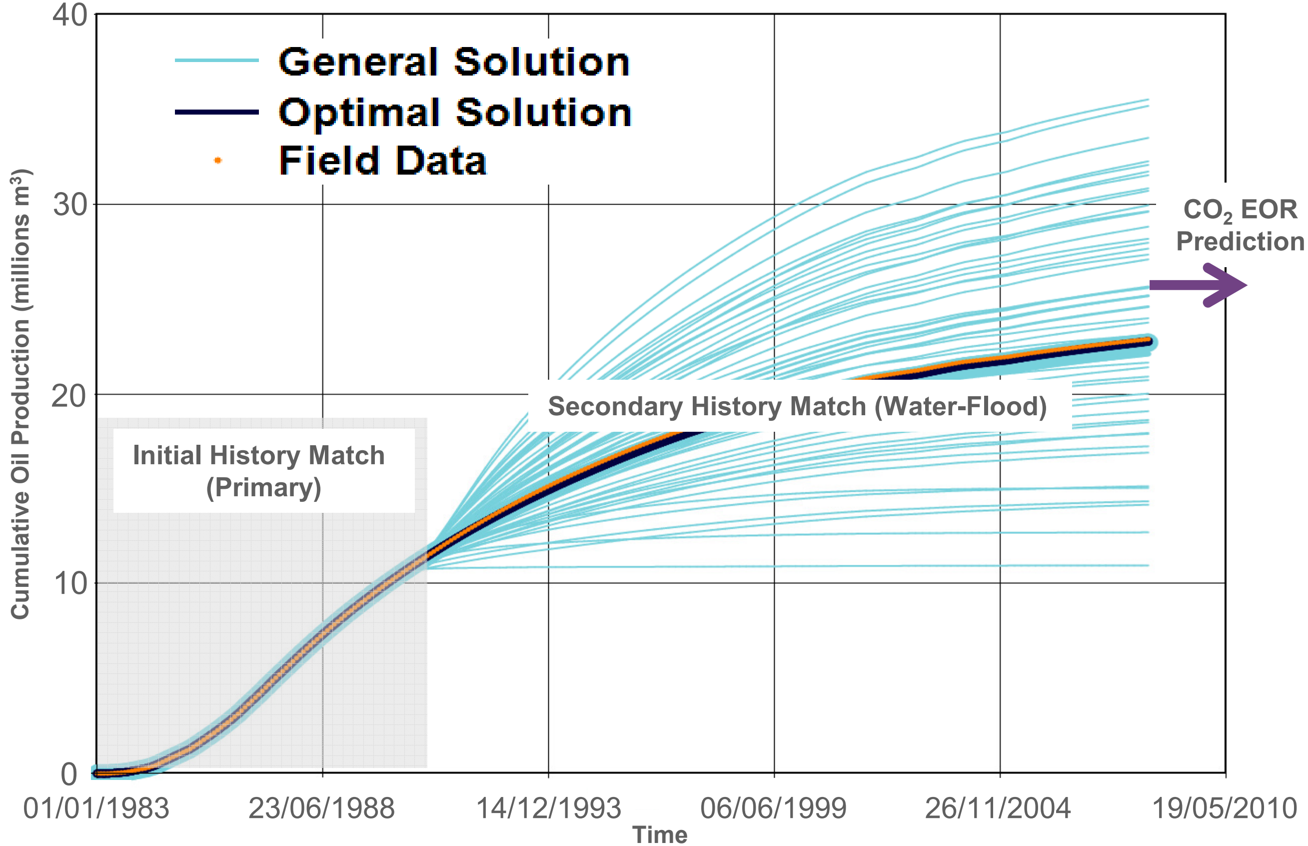
Case 2: Multiple-Stage History Match



Needed to match

- Bottom-hole pressures
- Cumulative oil production
  - Per well
  - Entire field
- From 1983 - 2008

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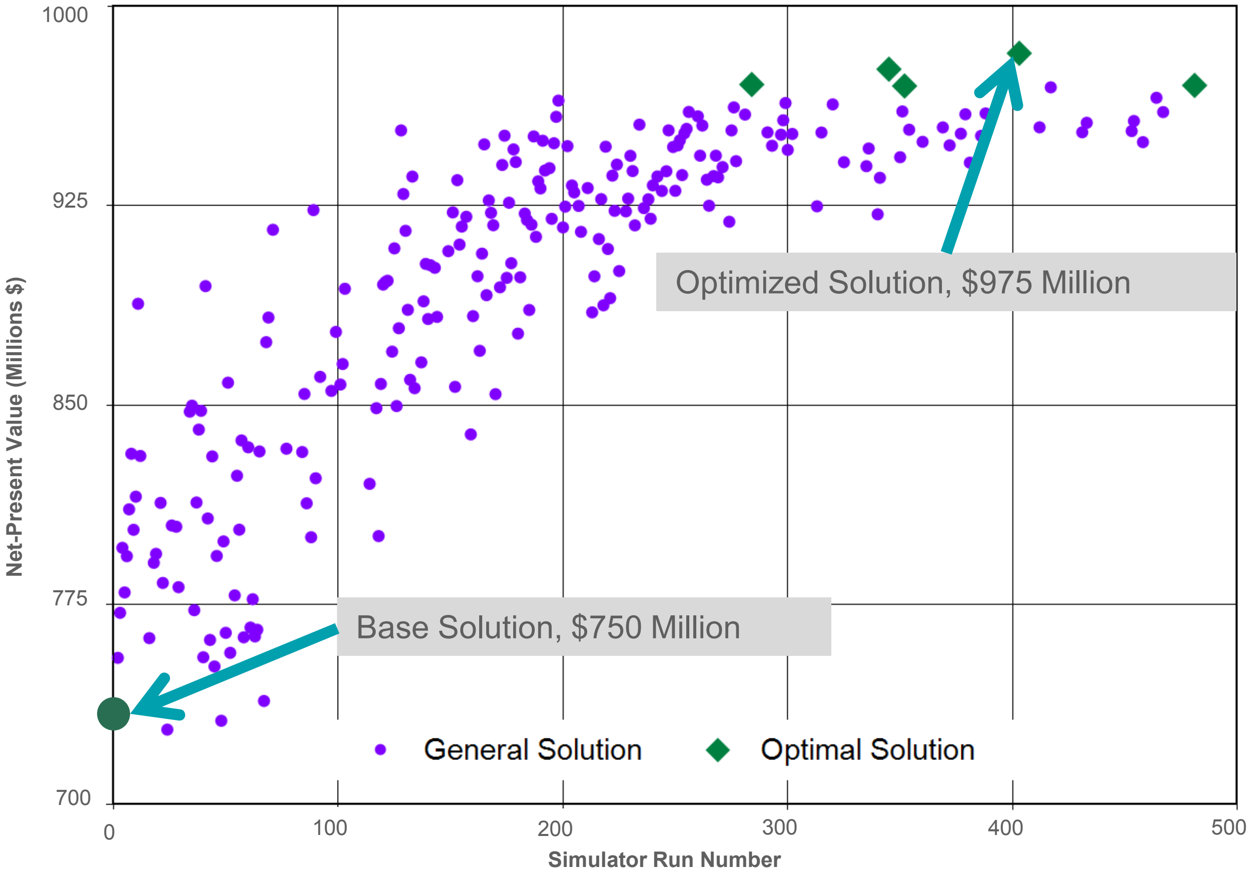
Case 2: Optimization of WAG Process



Optimized NPV

- Base NPV
  - **$750 Million**
- Optimized NPV
  - **$975 Million**
- Slug sizes
- Injection pressures
- Producer water-cut & GOR controls

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Case 2: Physics Included

EOS phase behaviour

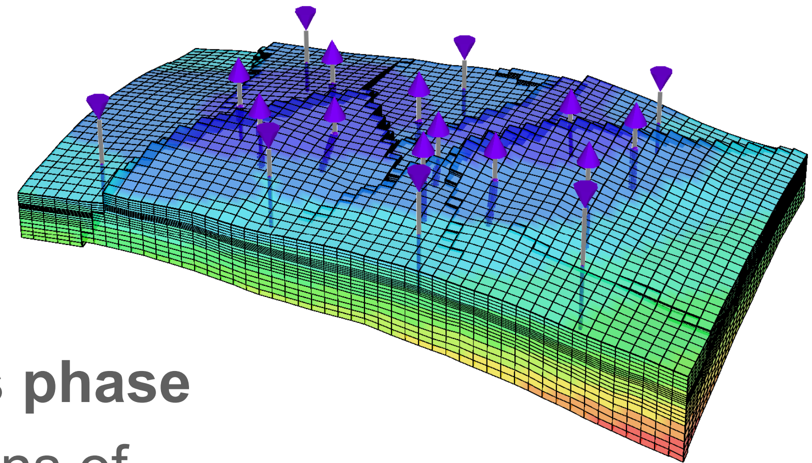
- Correctly accounts for phase changes of oil and CO_2

FCM and MCM determinations

- Viscosity alteration

Solubility of CO_2 in the aqueous phase

- Viscosity and density alterations of aqueous phase



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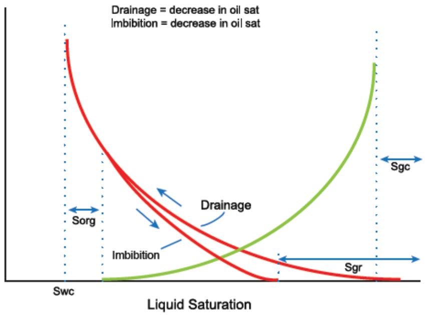
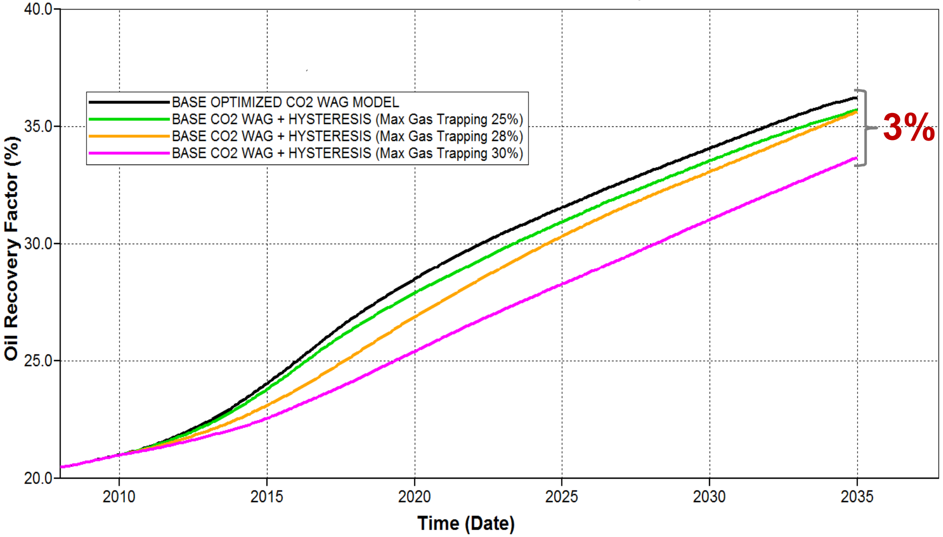
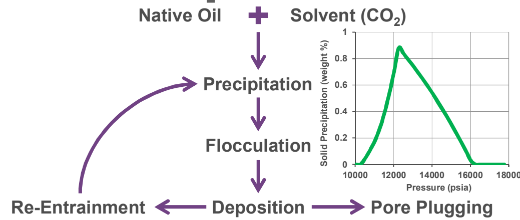
Case 2: Additional Considerations

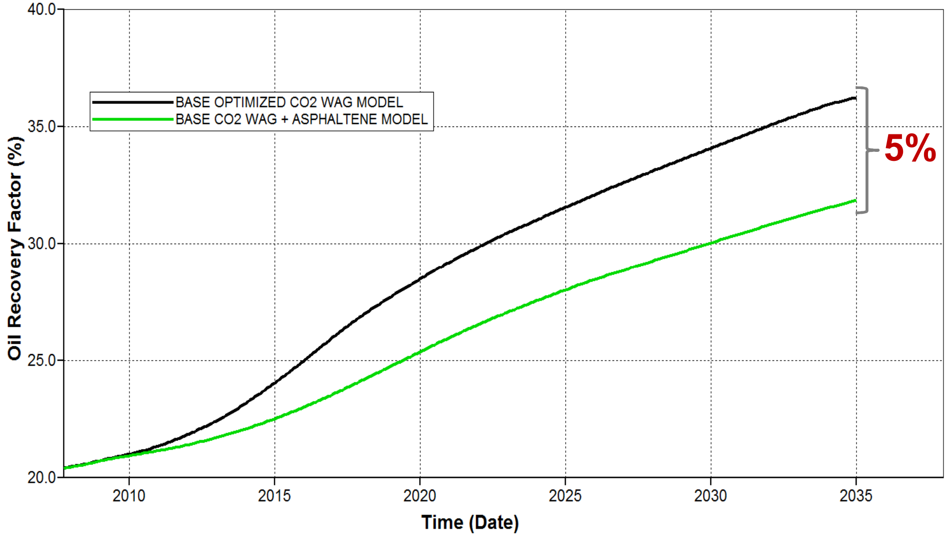
Hysteresis





Asphaltene Deposition





Capabilities for Carbon Management

GEM

- Geochemical EOS compositional simulator for CO_2 storage in saline aquifers

Modelling of CO_2 solubility and brine properties

- Solubility trapping

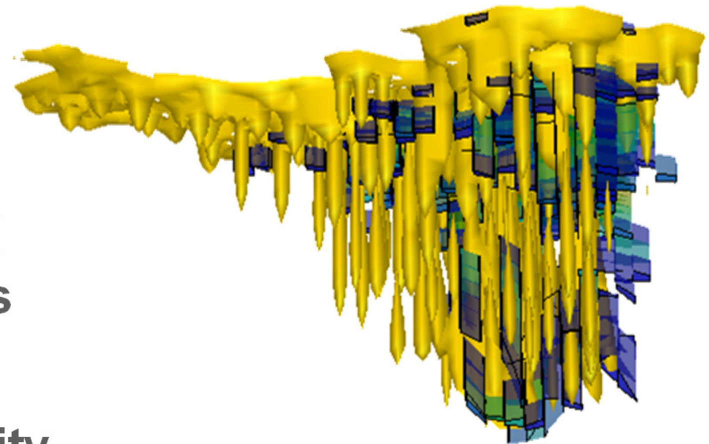
Relative permeability hysteresis

- Residual gas trapping

Aqueous chemical equilibrium reactions and mineral dissolution and precipitation kinetics

- CO_2 mineralization

Geo-mechanics to model the cap rock integrity based on stress/strain relationships



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Conclusions

- CMG accurately models CO_2 related processes and mechanisms
- PVT modelling and data matching (WinProp)
- GEM multiphase multicomponent EOS thermal flow simulator
  - CO_2 Flooding, WAG, Foam, Polymer, ASP, LSWI, …
  - Low Salinity + Miscible + Foam + ASP
  - **GEM** is **only commercial simulator** that models combination of processes
- Full geochemistry model (aqueous reactions, ion-exchange, mineral dissolution, …)
- Geomechanics Module
- Sensitivity study, history matching, optimization, uncertainty analysis (CMOST)
- **No other simulator/package can do all of this**!

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