Fractured Reservoir Characterization and Simulation Program at the University of Utah

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Chemical Engineering

U.S. DOE Project DE-FC26-04NT15531

Outline

- Overview
  - Research needs and solutions
  - Industry benefits
- Geologic connection
- Control-volume finite element method
  - Application to basement reservoir simulation
- Mixed finite volume method
  - Application to simulating complex heterogeneous domains
  - Thermal simulation
  - Representation and simulation of multilaterals
- Accomplishments

Overview

Research Needs and Solutions

PROBLEMS

Complex domains with fractures, faults

Faster, efficient finite-element simulators

Different recovery mechanisms over reservoir life

Complicated wells (multilaterals, MRC wells)

Rapid validation of generated fracture networks

No standards for components in a simulator

Difficulty of parallel computing

SOLUTIONS

Use of unstructured grids (finite-element) body-fitting gridding

Multigrid, multiscale methods
Jacobian calculations
Separation of reservoir model and the numerical method

Addition of modular thermal and compositional modules for use with finite-element grids

Innovative well models for unstructured grid systems

Rule-based algorithms to generate data, Grid and simulate rapidly and Validate using available field data

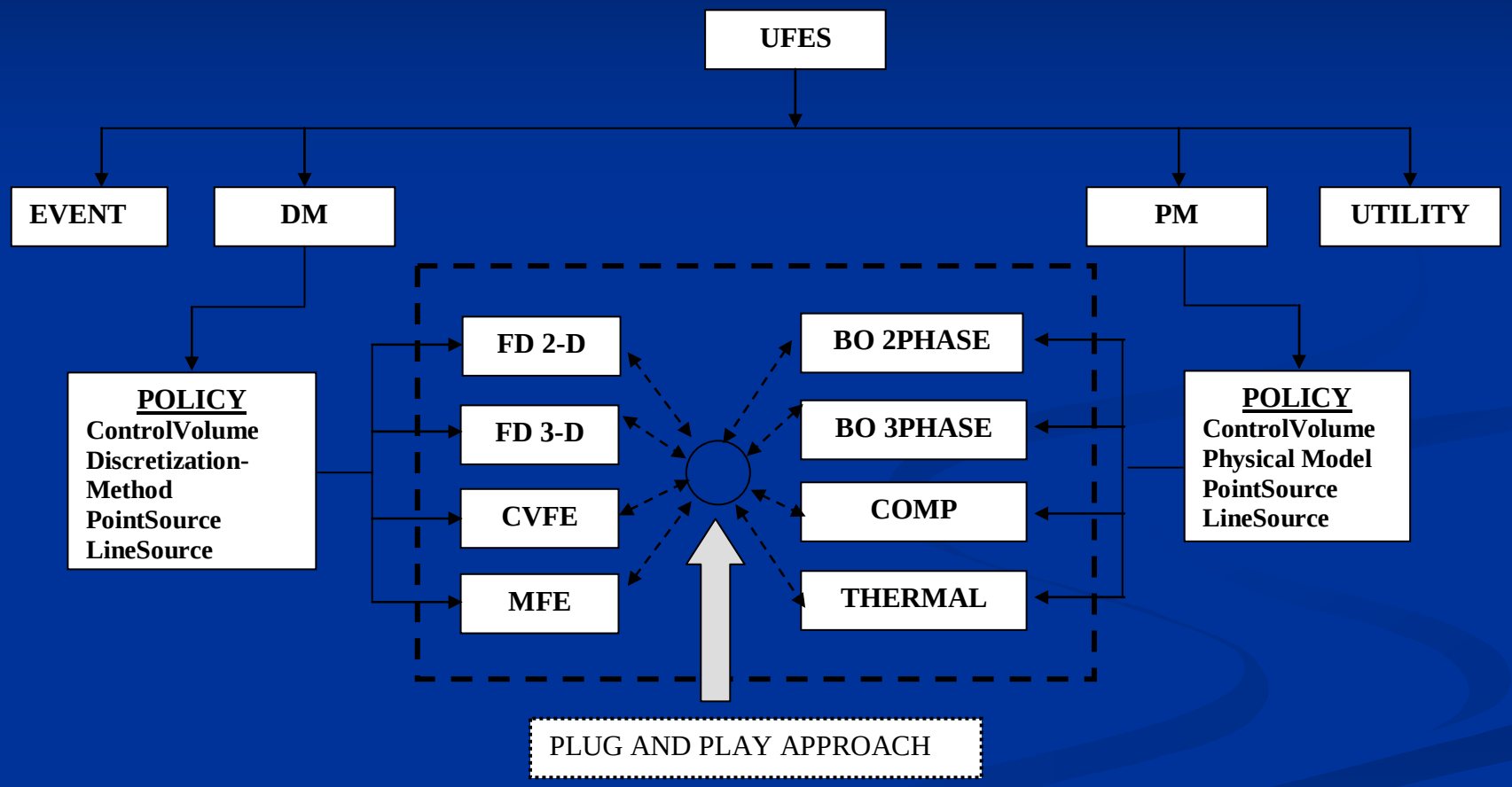
Use of Common Component Architecture, a scheme pioneered by the U.S. DOE

Data distribution and parallel computing at the touch of a button for heterogeneous systems

Benefit to the Industry

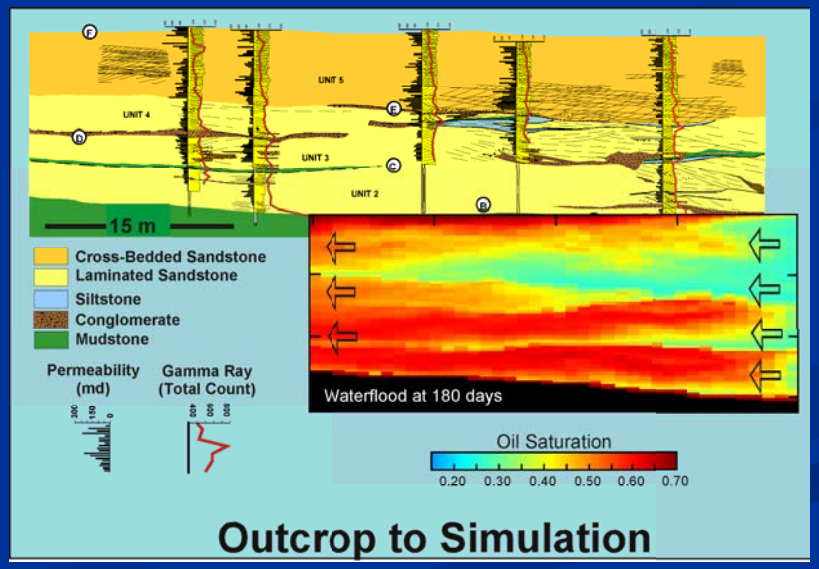
- Recognition that faults and fracture networks matter
  - Incorporation of realistic fracture networks in simulations
- Simulation of domains of complicated geometries
- Well modeling
  - Complex geometry, multilaterals, maximum reservoir contact
- Reservoir life-cycle modeling
- Combining various physical models with different discretization models
- Standardization using Common Component Architecture
- Parallel computing in unstructured grids
- Consideration of technologies in CFD, medical applications, etc.

Structure of the University of Utah Finite Element Simulators (UFES)



Focus

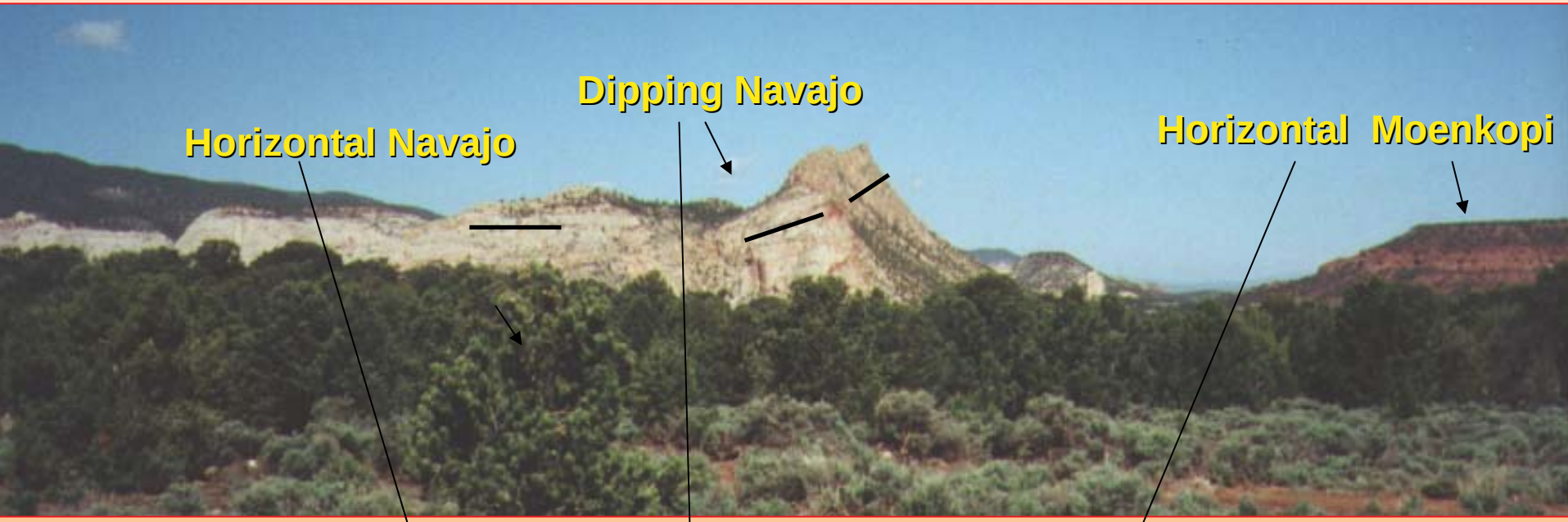
- Emphasis on systems of complex geometry
- Fractured/faulted systems
- Characterization extremely important

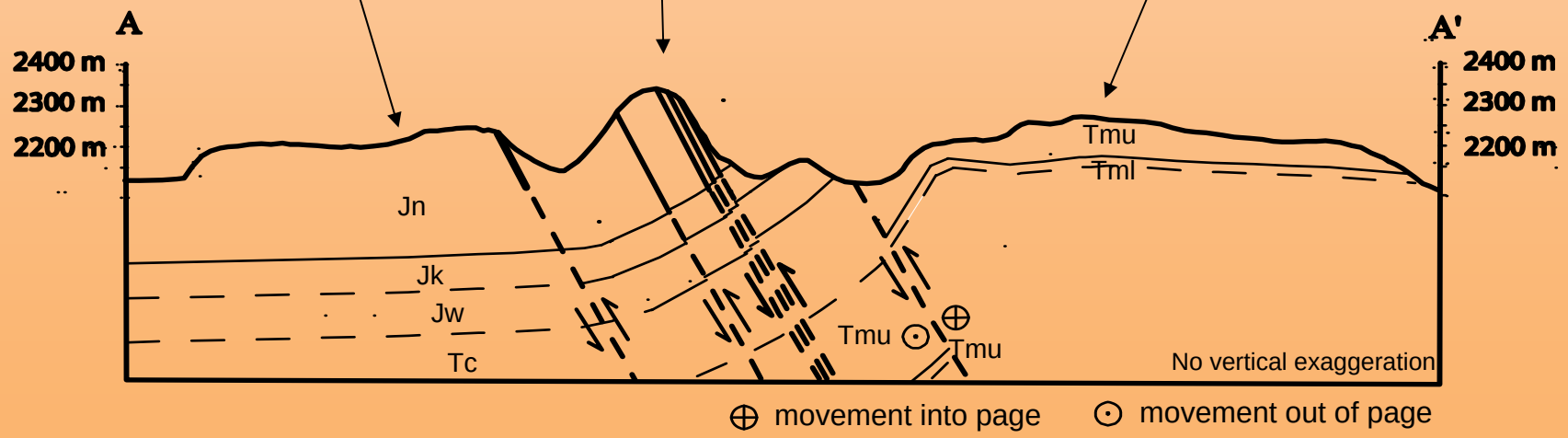


Geologic Connection

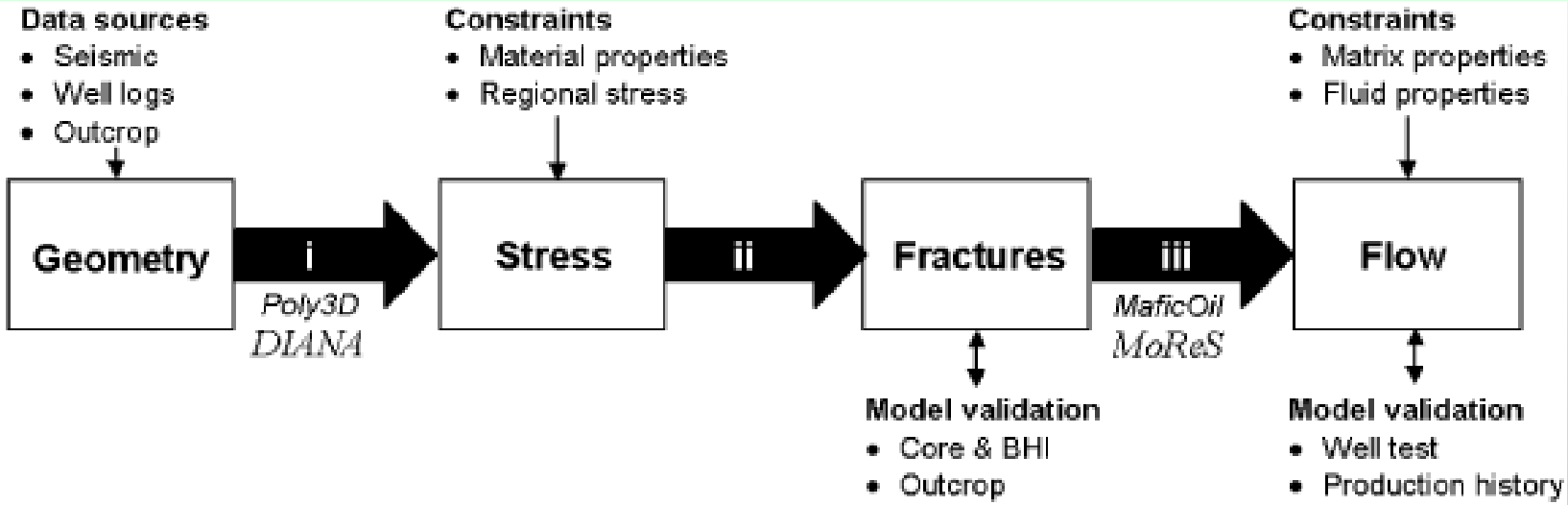
- Craig Forster – University of Utah
- Jim Evans – Utah State University
- Golder Inc., Seattle, Washington
  - Makers of Fracman and FRED

Cocks Comb cross section



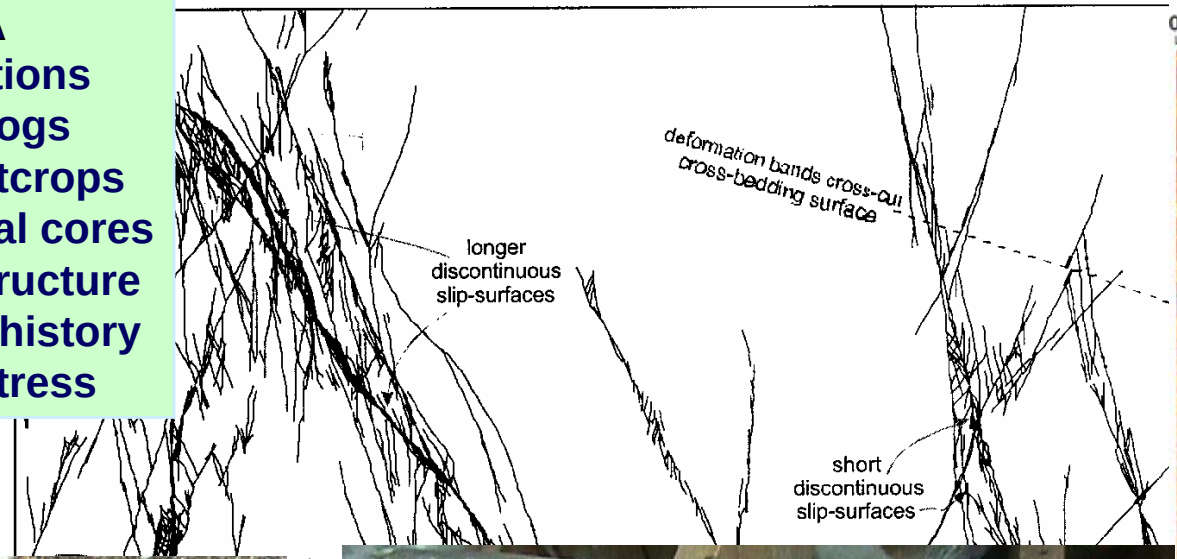


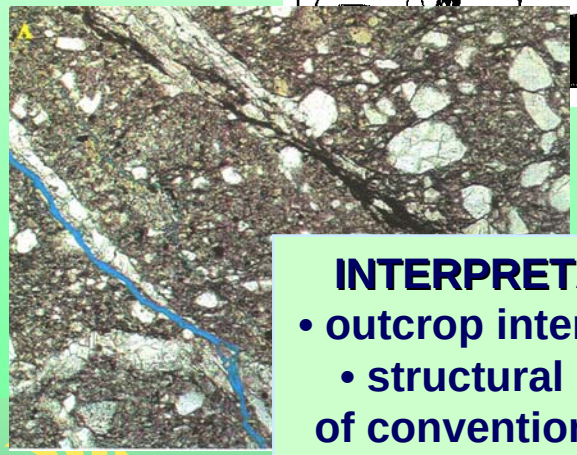
Seismic attribute analysis

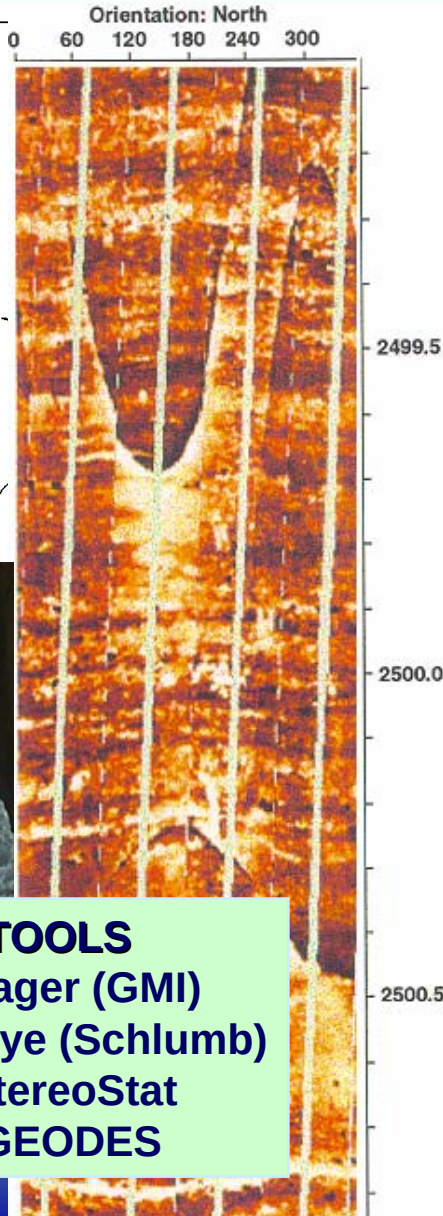


Identify Critical Tectonic Elements

DATA
- thin sections
- image logs
- analog outcrops
- conventional cores
- regional structure
- structural history
- *in situ* stress







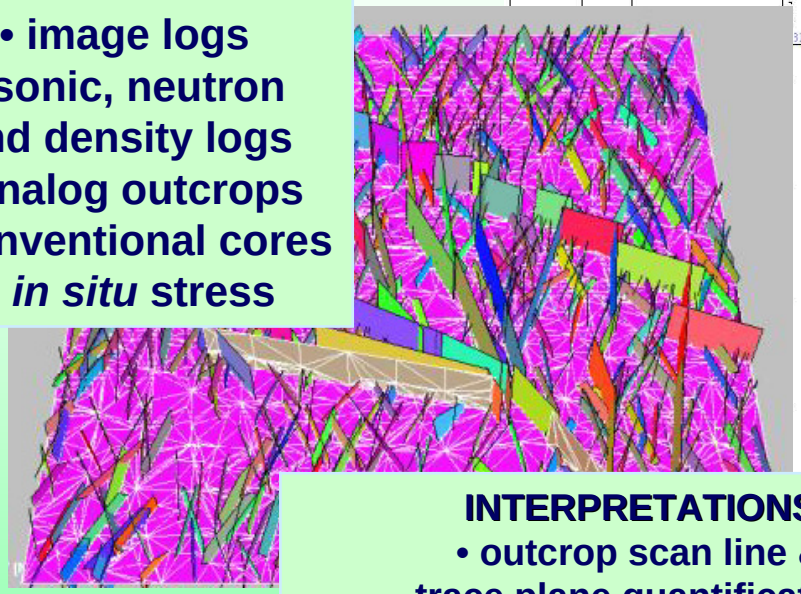
INTERPRETATIONS
- outcrop interpretation
- structural logging of conventional cores
- microfracture analysis
- image log analysis
- dip data analysis

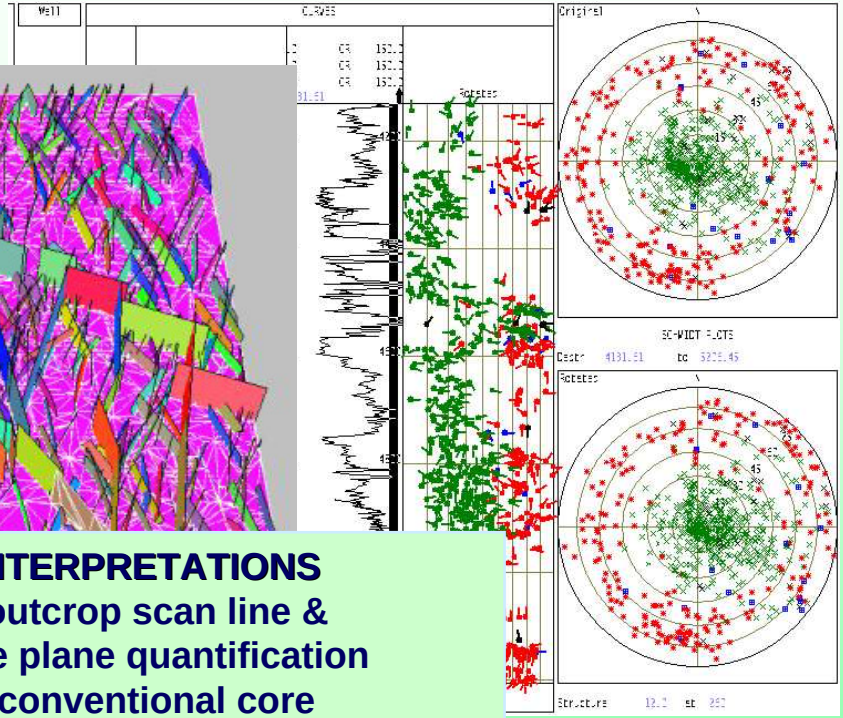
TOOLS
- Imager (GMI)
- Well-eye (Schlumb)
- StereoStat
- GEODES

GEOSCI
TRAININ
ALLIANCE

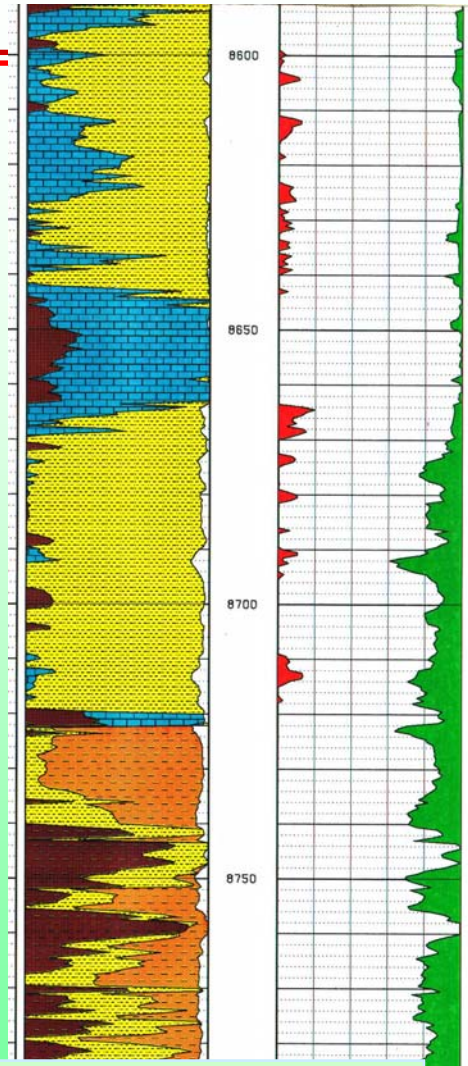
Quantify Critical Damage Elements

DATA
- thin sections
- image logs
- sonic, neutron and density logs
- analog outcrops
- conventional cores
- *in situ* stress





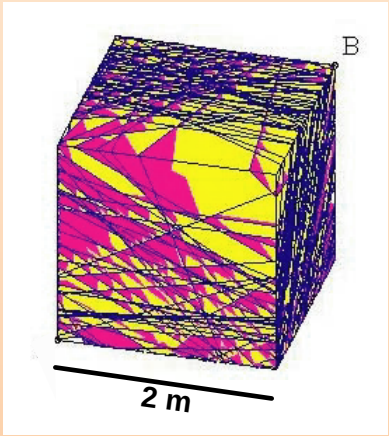
INTERPRETATIONS
- outcrop scan line & trace plane quantification
- conventional core fracture frequency quantification
- microfracture aperture & Ø quantification
- image log fracture frequency analysis
- DFN model construction & validation

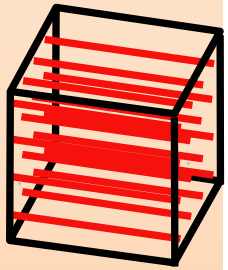


TOOLS
- FRACMAN
- Various petrophysical software systems

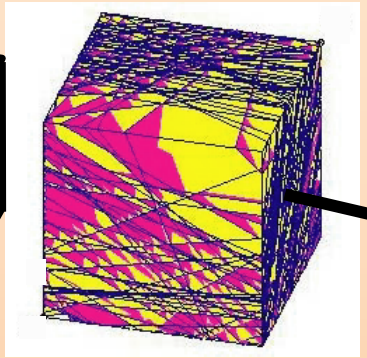
GEOSCIENCE TRAINING ALLIANCE

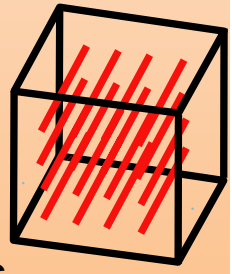
Deformation Band (DB) Networks



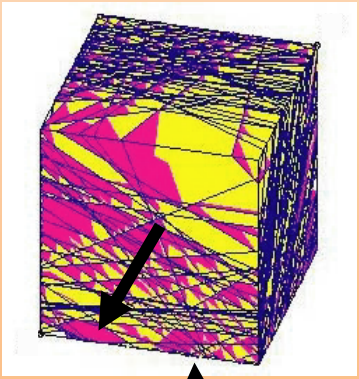


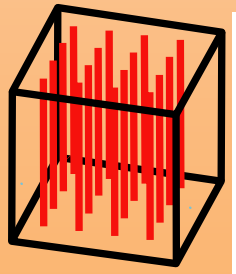
14 md



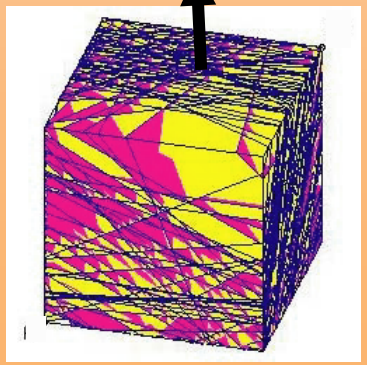


7 md



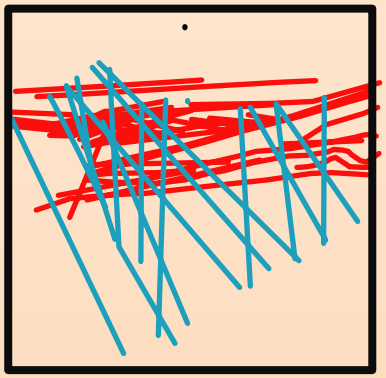


22 md



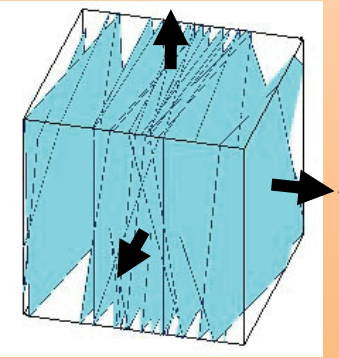
K_{eff} = Harmonic mean
with 500 md SST,
1 md DB,
1 mm thick DBs

Fracture Network Models
Using FracMan by Golder Assoc.



Joint Networks

2508 md



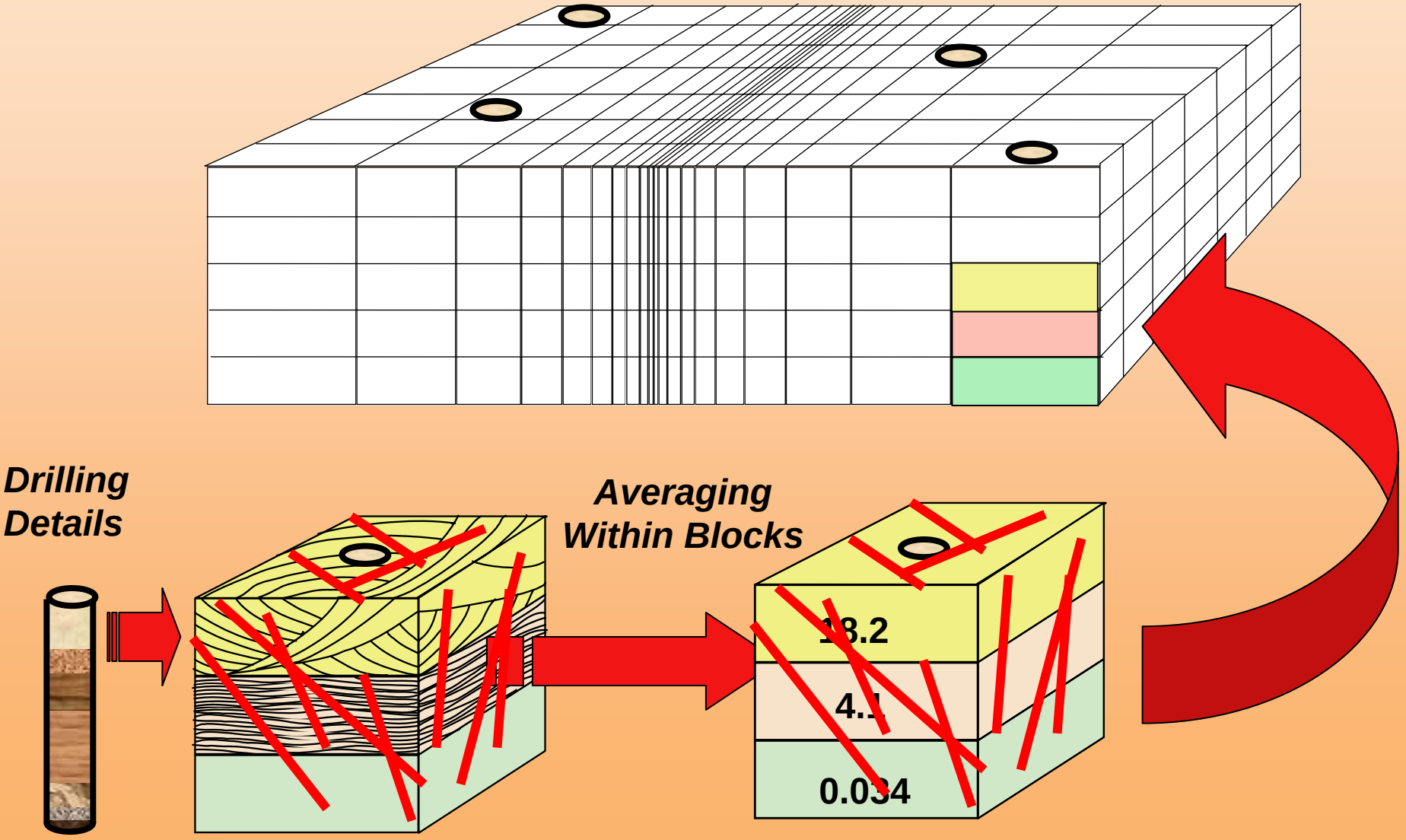
379 md

3631 md

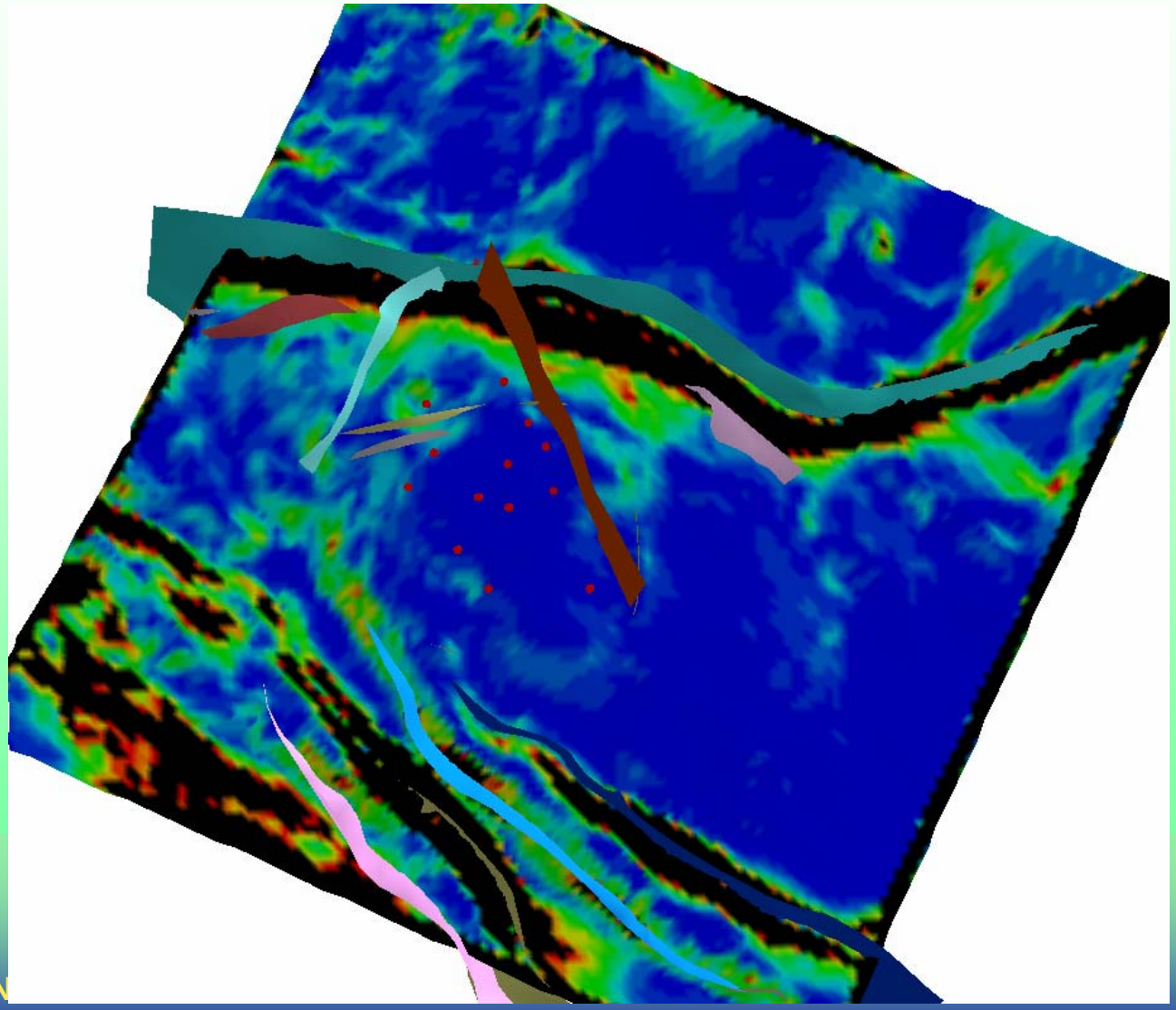
K_{eff} = Oda continuum
with 500 md SST,
100 μm fracture,
25 fractures/m

Assigning Numbers

(at and between drill holes)



Analysis of strain in rocks

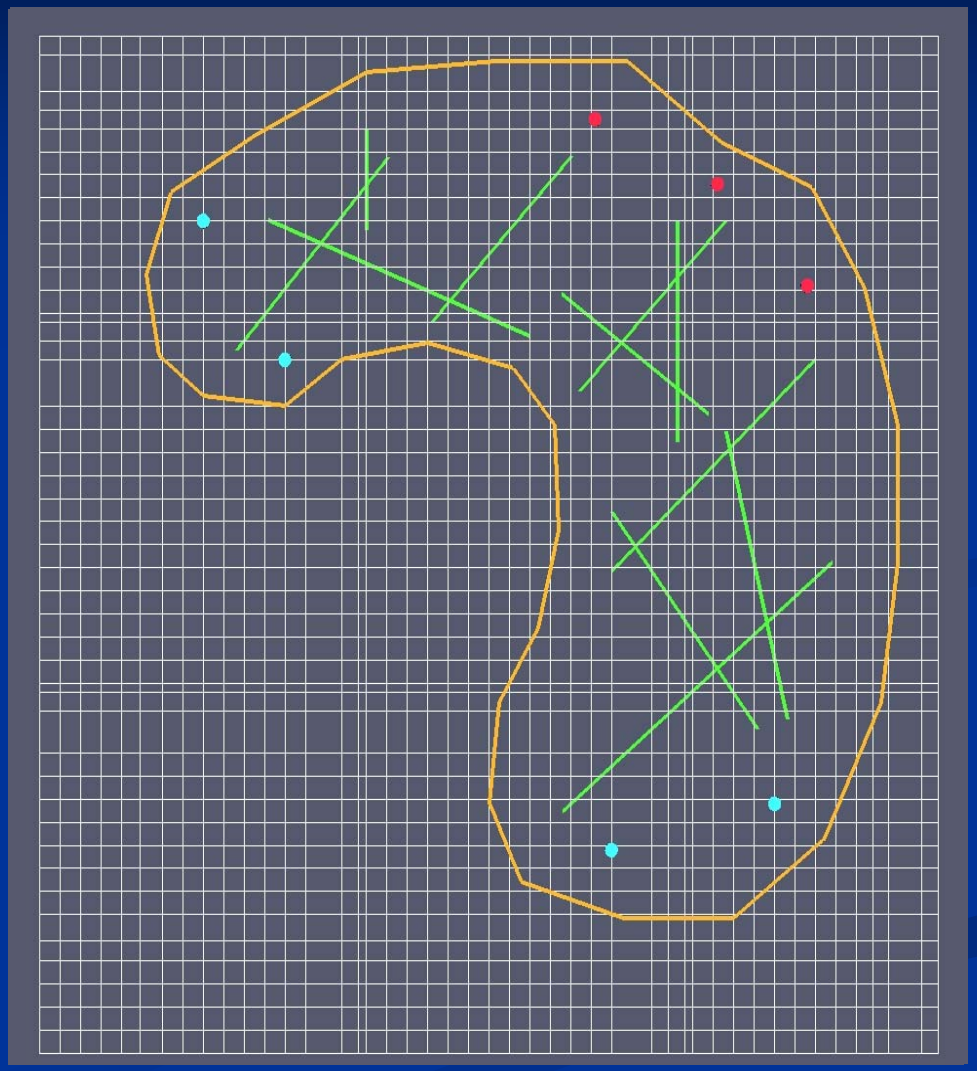


Motivation

Complicated boundary

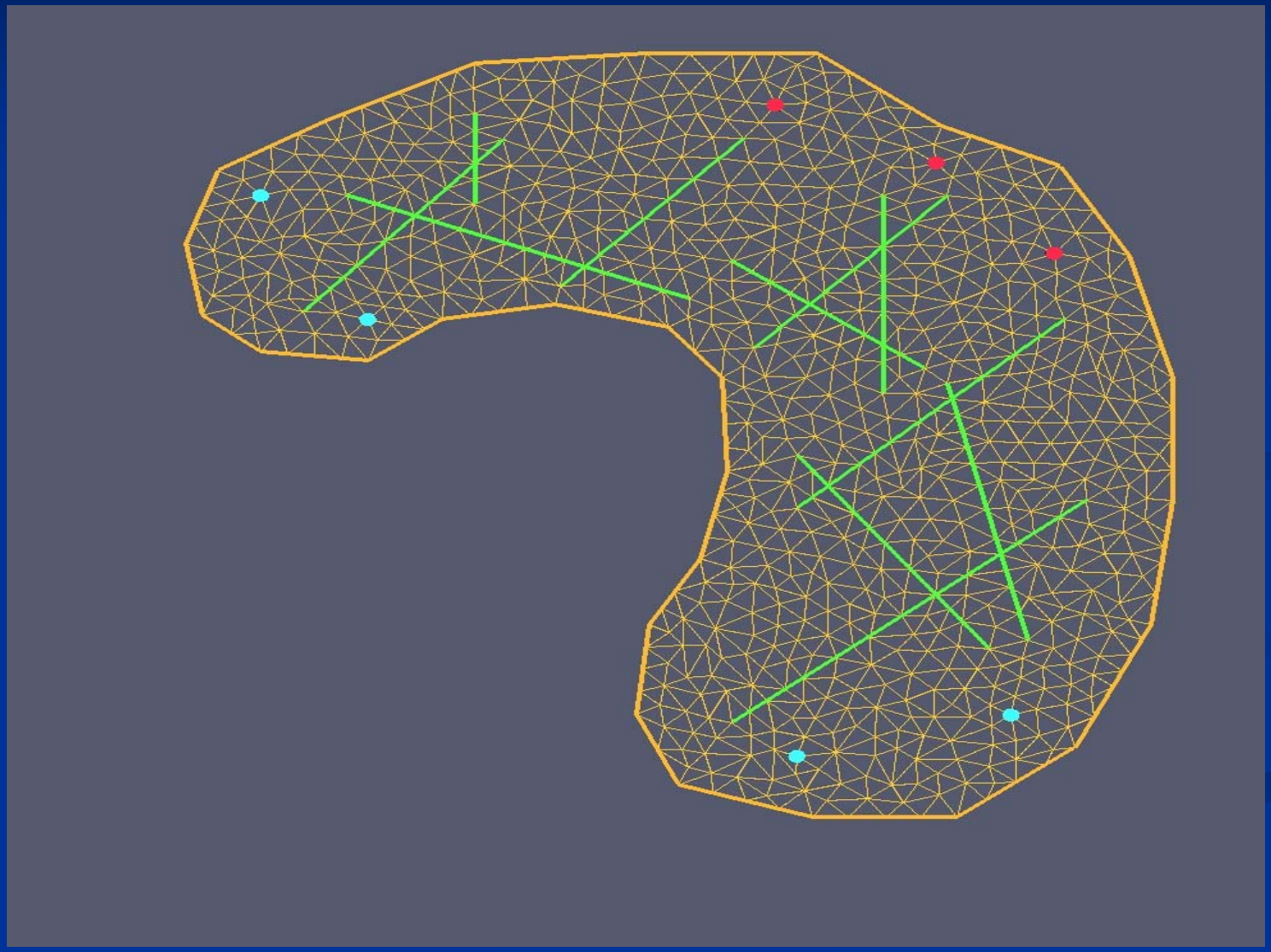
– domain with fractures

– difficult to simulate with existing simulators



Attempt to create a structured mesh

The same domain gridded using a finite-element mesh



Control Volume Formulation

Three-phase flow in porous media

$$-\nabla \cdot \underline{u}_0 = \frac{\partial}{\partial t}\left(\frac{1}{B_o}\phi S_o\right) + q_o$$

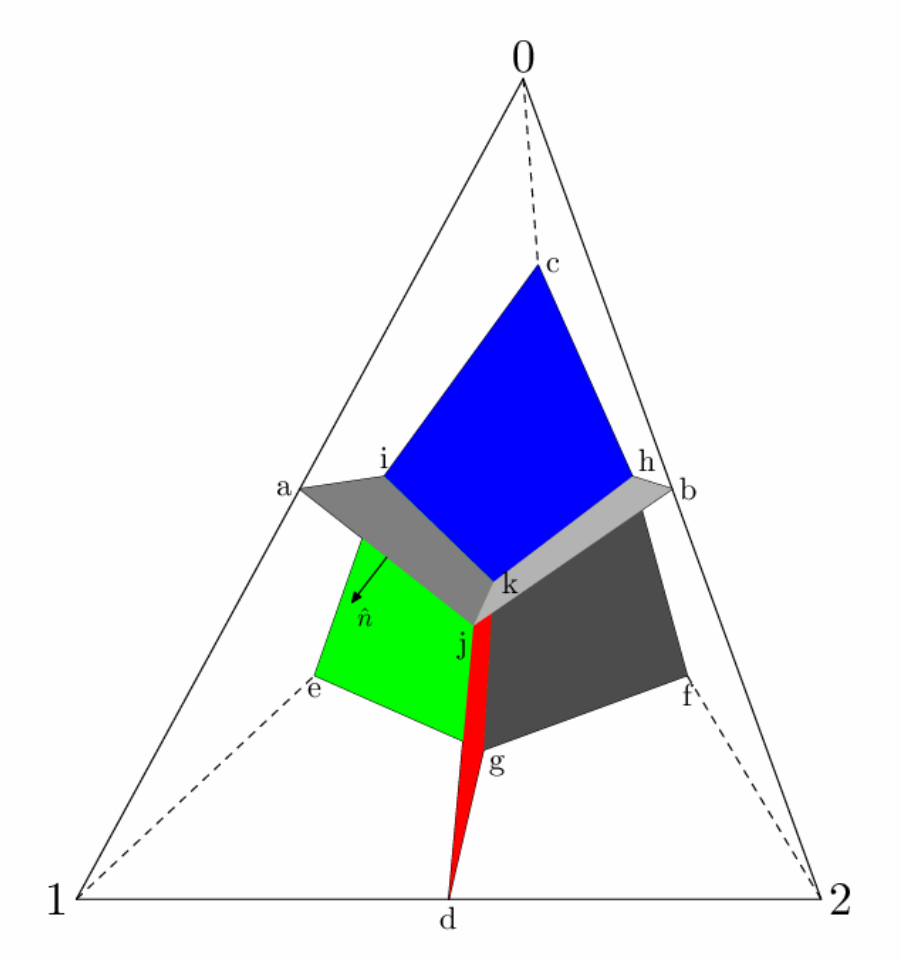
$$-\nabla \cdot \underline{u}_w = \frac{\partial}{\partial t}\left(\frac{1}{B_w}\phi S_w\right) + q_w$$

$$-\nabla \cdot \left(R_s \underline{u}_o + \underline{u}_g\right) = \frac{\partial}{\partial t}\left(\frac{R_s}{B_o}\phi S_o + \phi \frac{S_g}{B_g}\right) + R_s q_0 + q_{fg}$$

A tetrahedral element with associated control volumes

In the control-volume formulation, the fluid potential and saturation values are defined on the vertices of the tetrahedron.

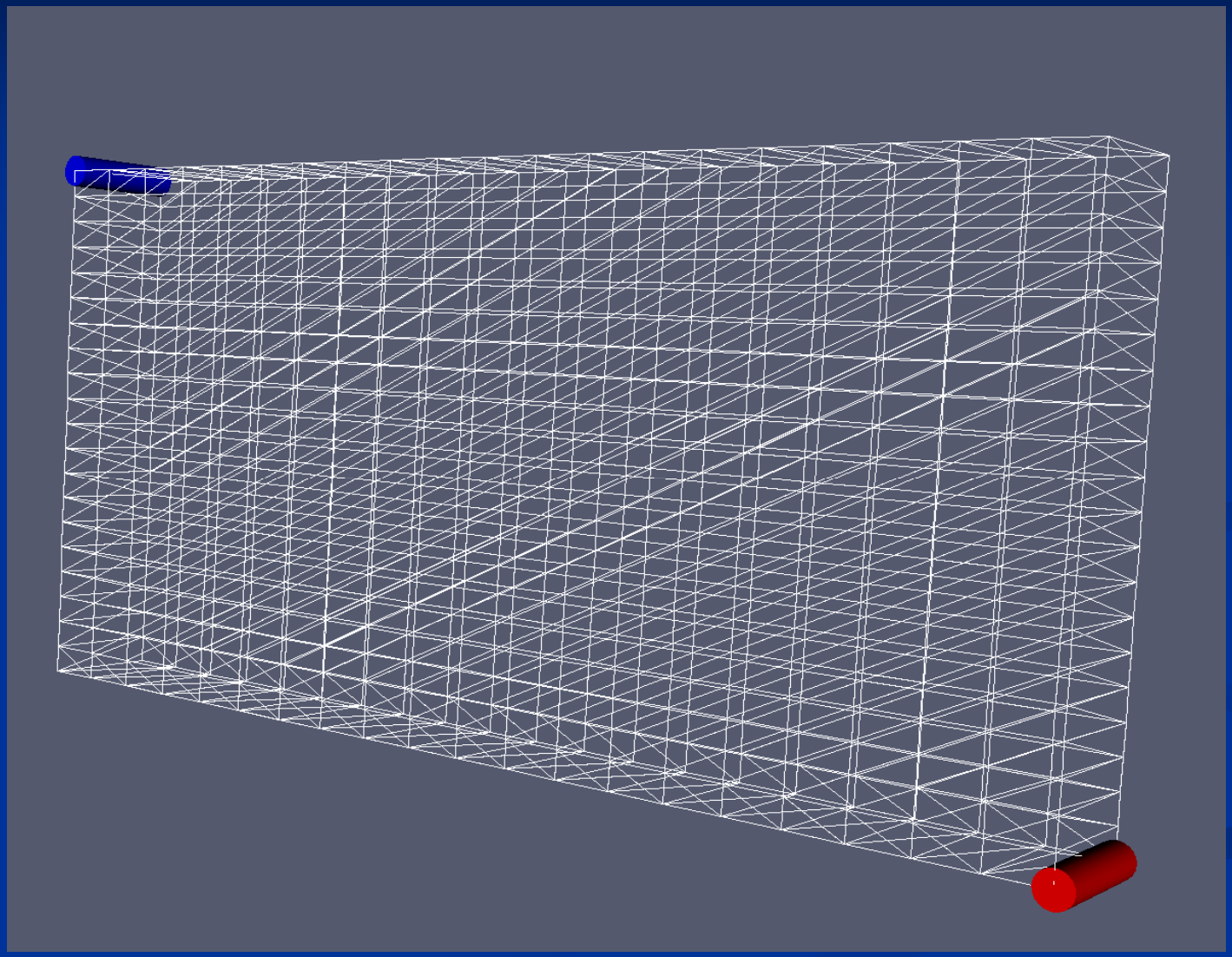
The fluid potential value in the tetrahedron is interpolated using the interpolation functions. The fluid saturation value is calculated for each control volume from the solution of the residual equations.



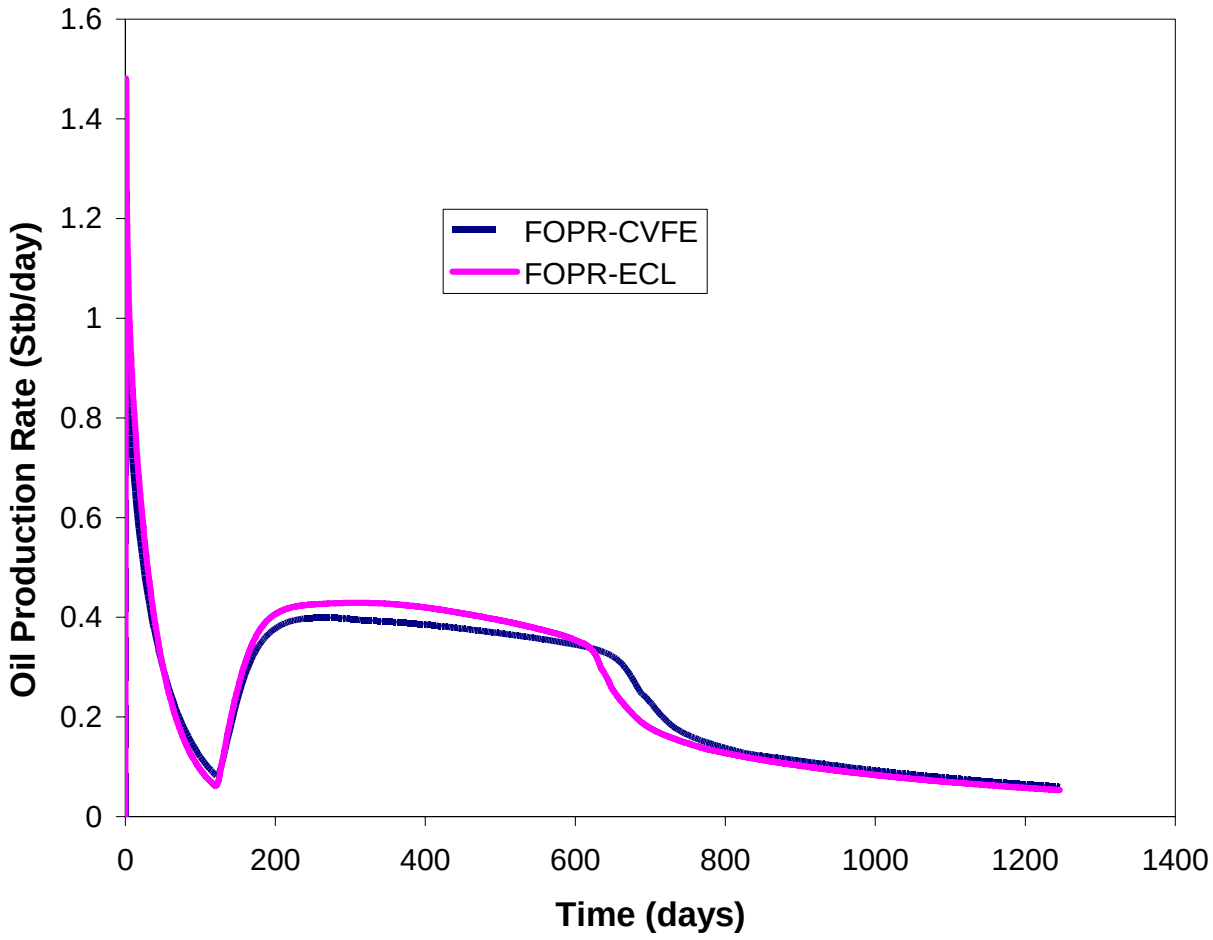
Three-dimensional, three-phase simulations Benchmarking

Domain	10 feet x 100 feet x 50 feet
CVFE simulations: Number of tetrahedrons	2400
Eclipse simulations: Number of blocks	400
Horizontal injector	At the top, (shown in blue)
Horizontal producer	At the bottom, (shown in red)
Initial reservoir pressure	3300 psia
Initial bubble point pressure	3200 psia
Production bottom hole pressure	2900 psia
Primary production for	120 days
Water injection pressure	3300 psia
Water injection continued until	A water cut of 80% obtained

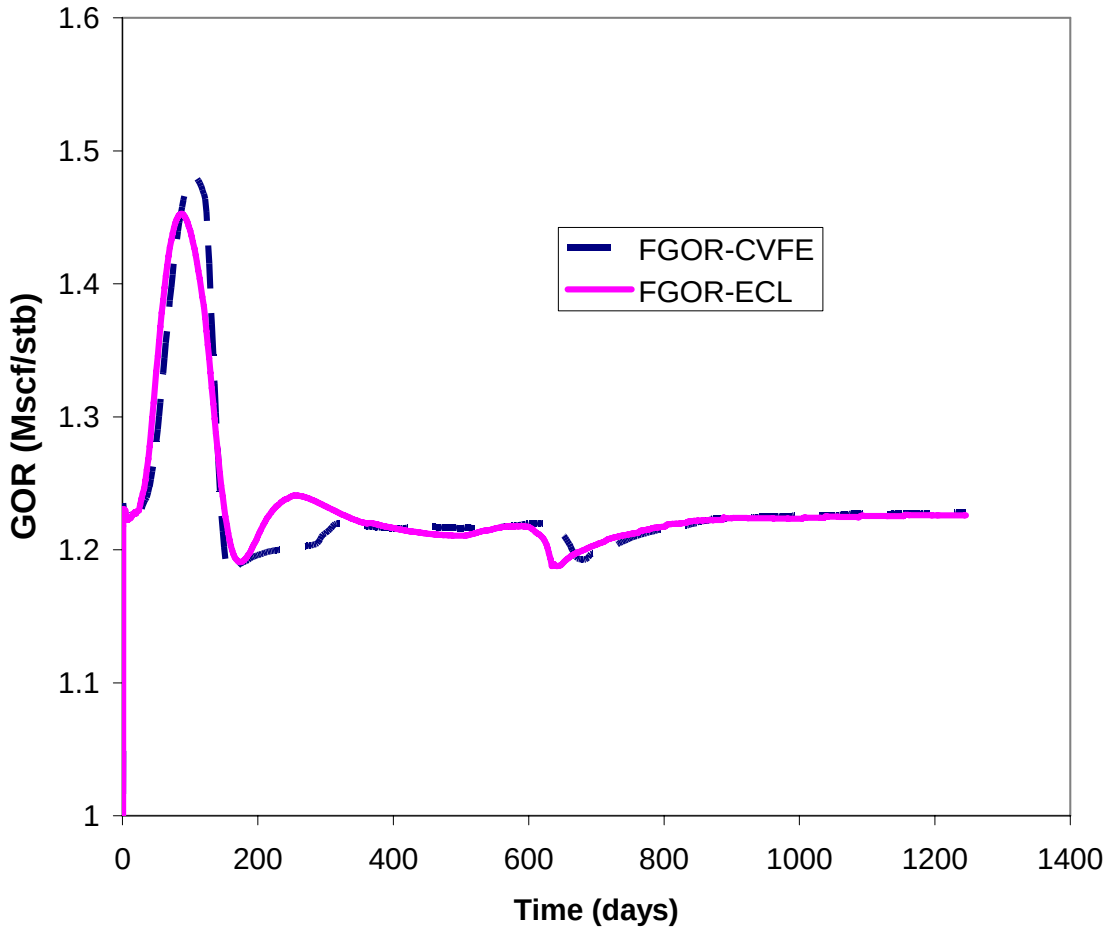
The regular domain using a tetrahedral mesh



Oil Production Rate



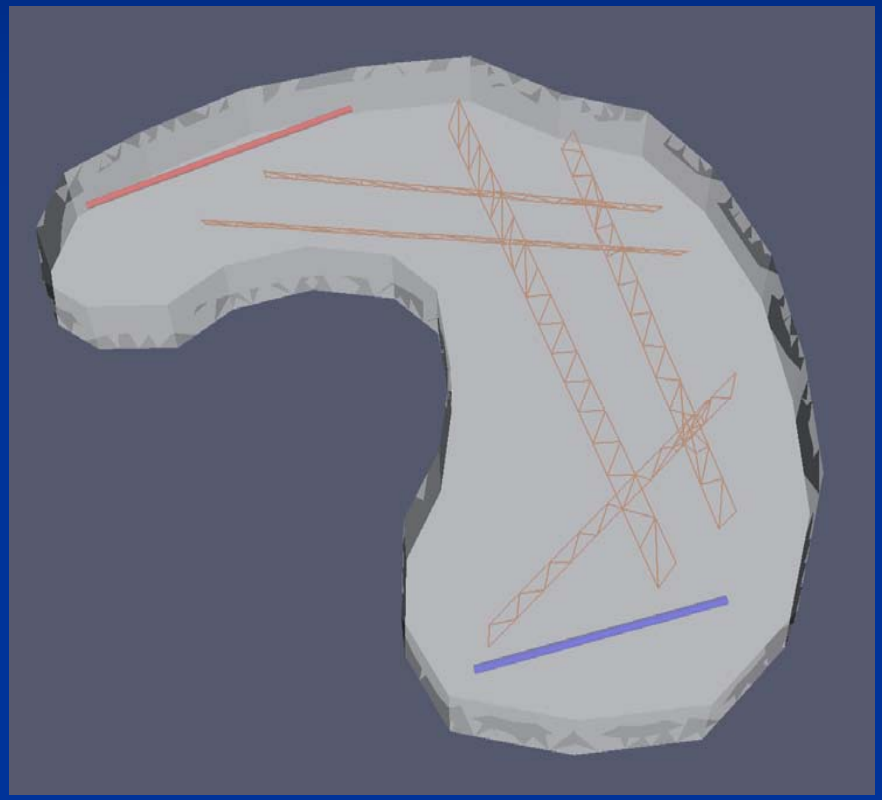
Gas-Oil Ratio



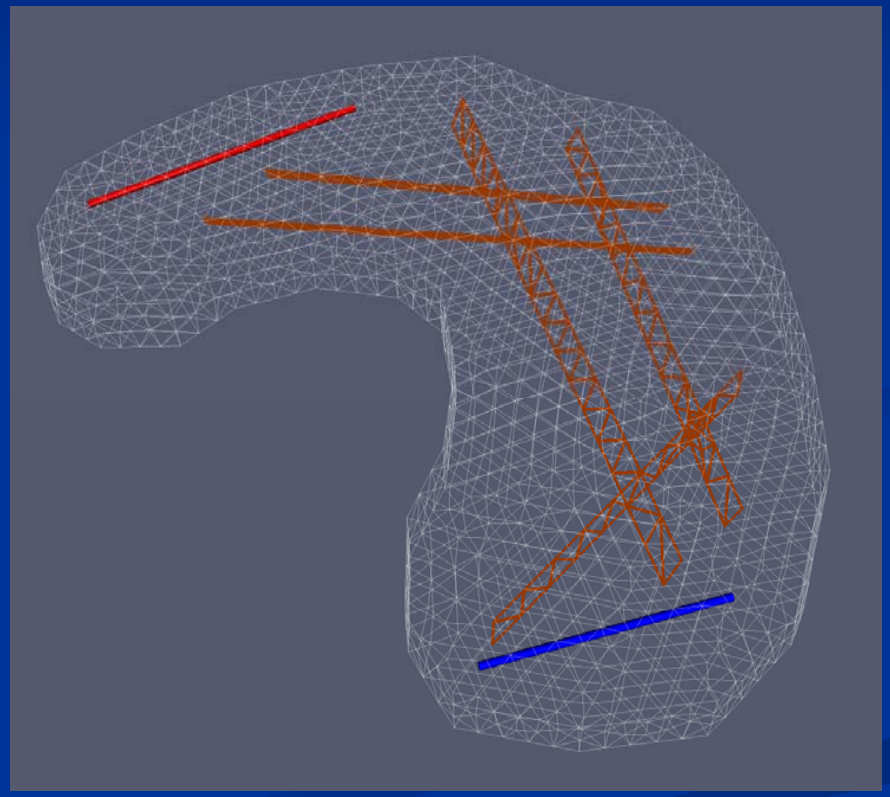
Three-dimensional, three-phase simulations with a complex domain

- Horizontal wells, injector shown in blue, producer shown in red
- Partially penetrating and tilted fractures

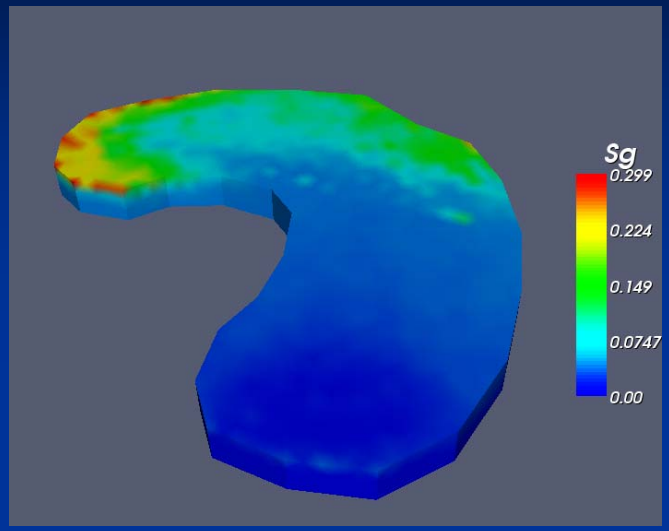
The three-dimensional domain

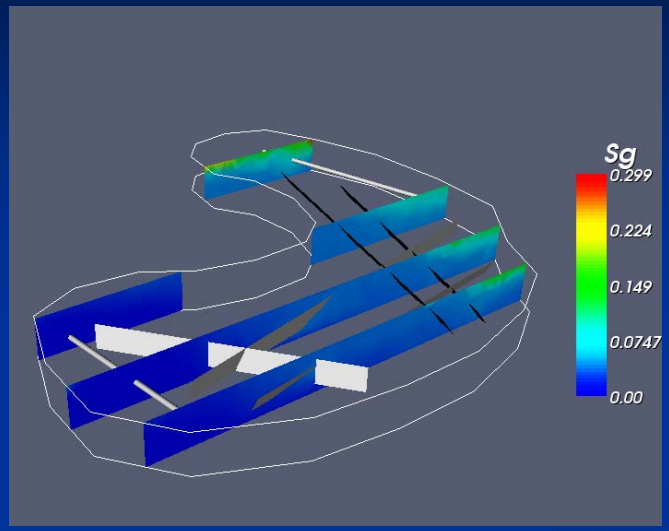


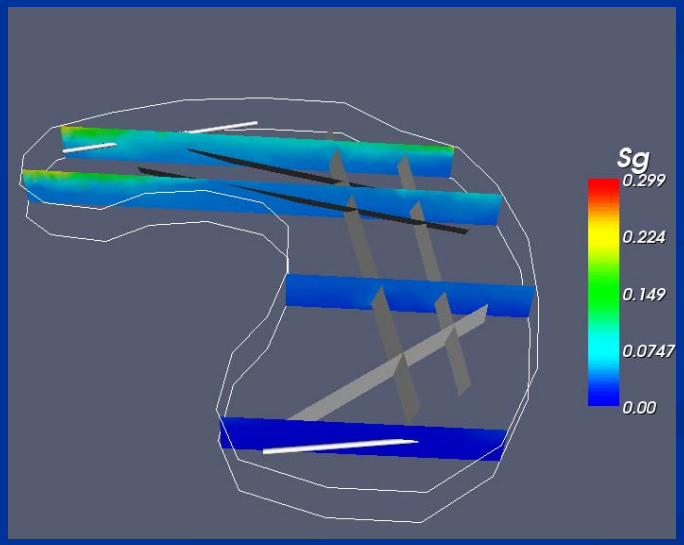
The tetrahedral mesh



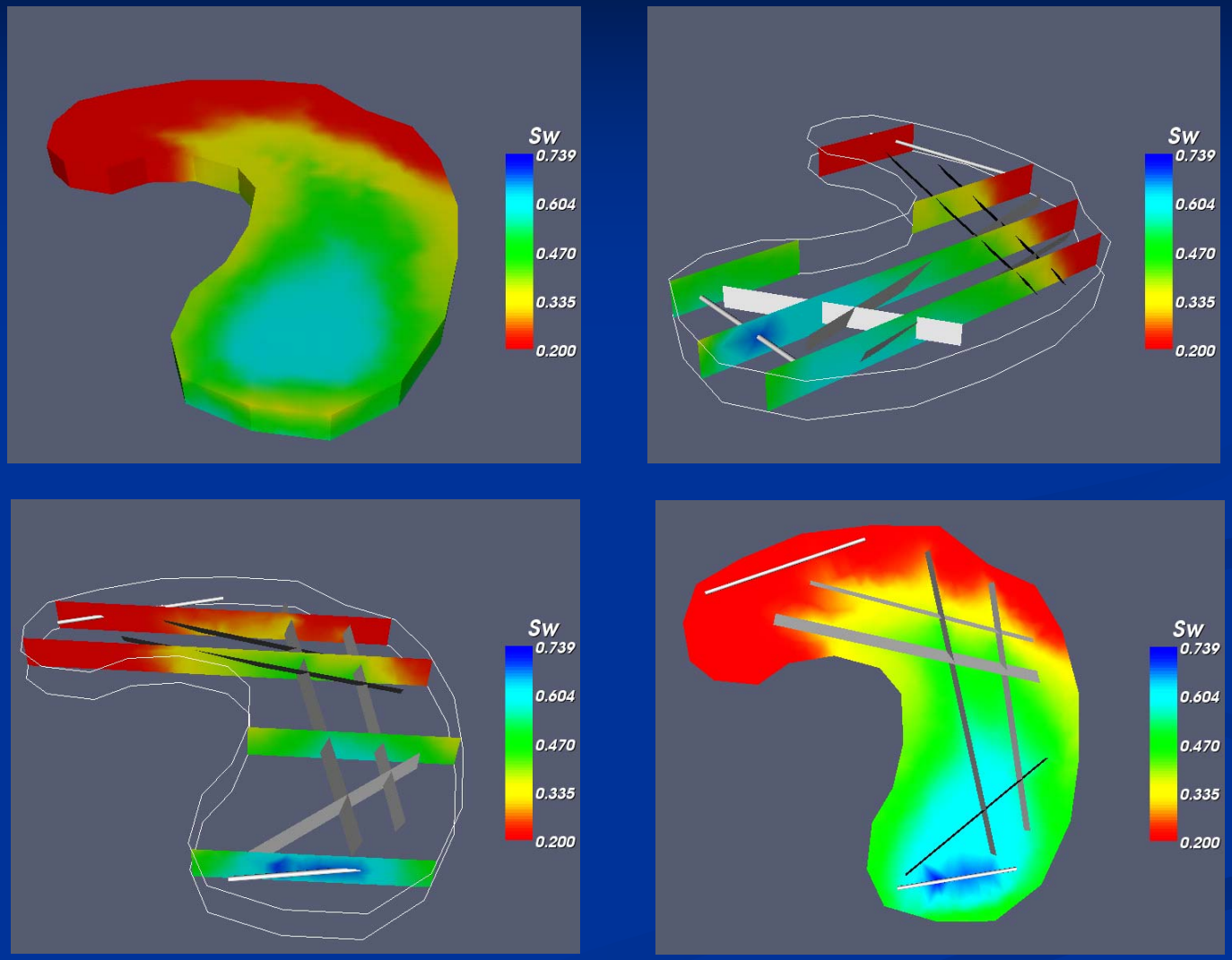
Gas saturations at 953 days







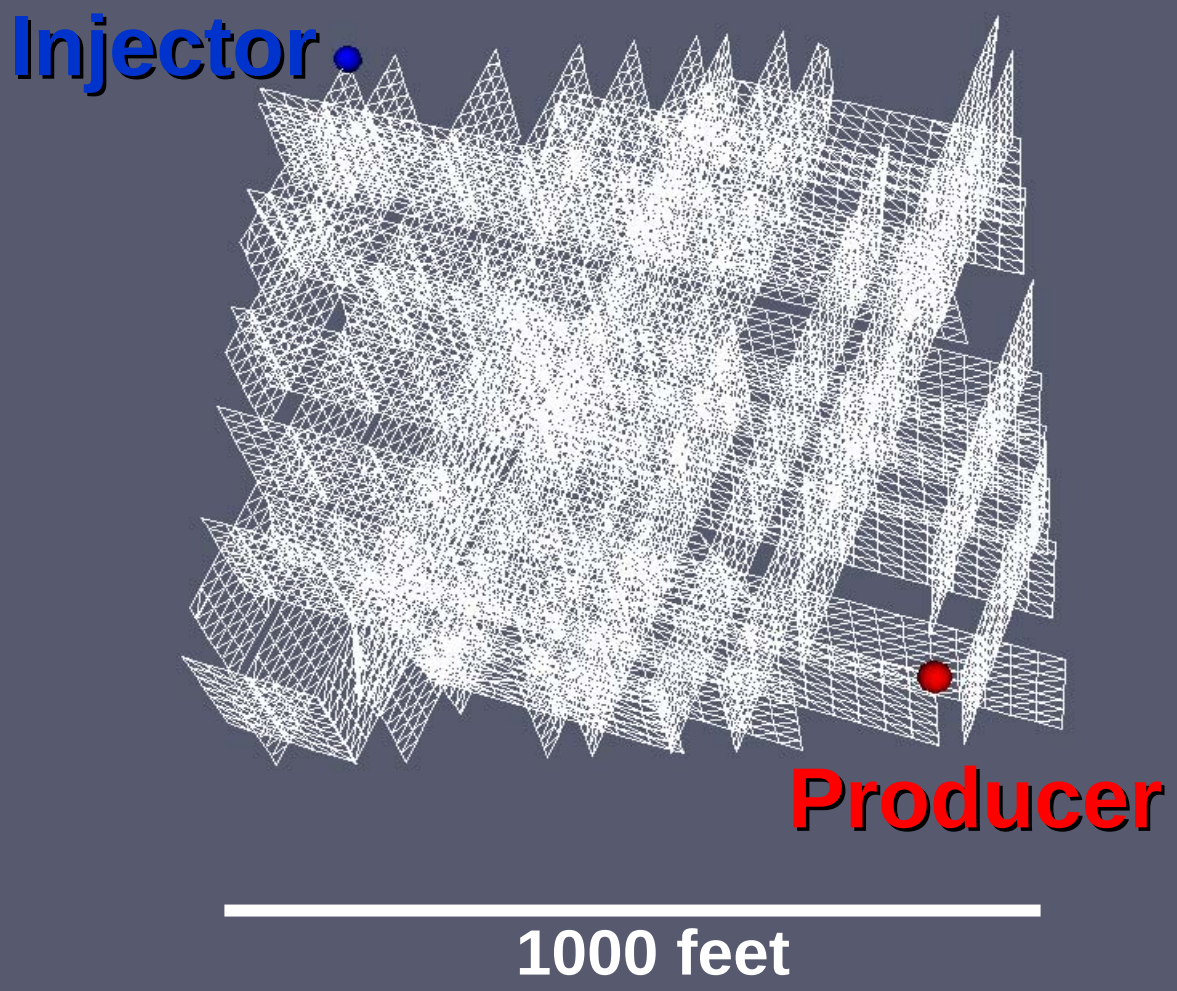
Water saturations at 3431 days, some channeling in the Fractures, but good sweep



Three-dimensional, three-phase simulations in networks of discrete fractures and faults

- Basement reservoir
- Fractures and mesh generated by Golder using FRED

Fracture Domain Triangular Mesh



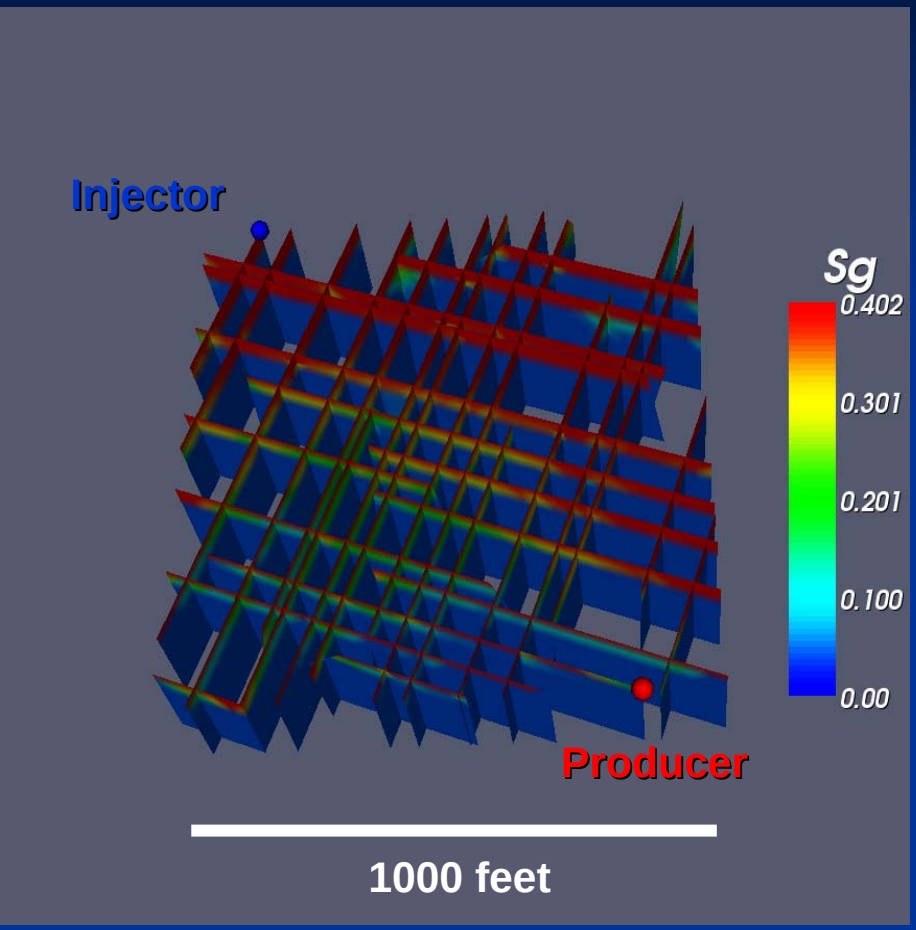
Dimensions and Other Parameters

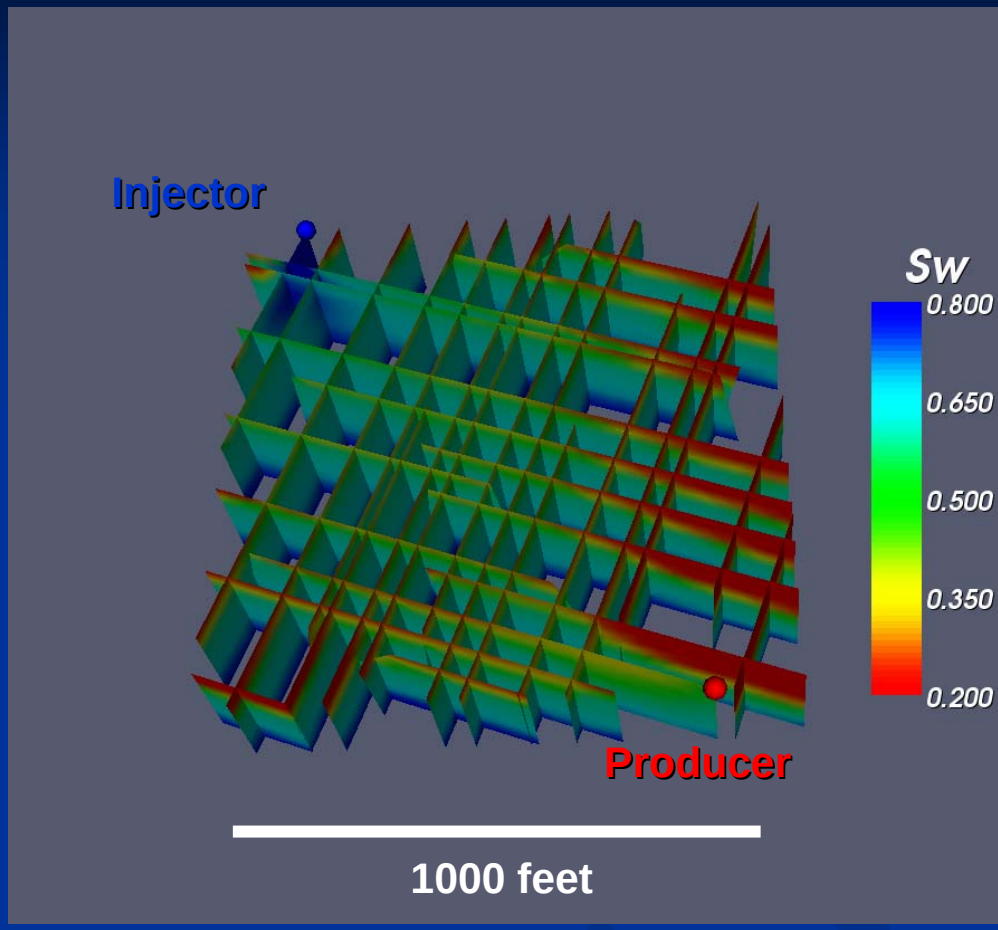
Domain	1000 feet x 1000 feet x 200 feet
Fracture thickness	0.5 foot
Fracture permeability	1000 md
Number of fractures:	31
CVFE simulations: Number of triangle	14939
Injector	At the top, (shown in blue)
Producer	At the bottom, (shown in red)
Initial reservoir pressure	3300 psia
Initial bubble point pressure	3200 psia
Production bottom hole pressure	2300 psia
Water injection pressure	4300 psia
Primary production for	300 days

Cases Examined

- Base case (homogeneous 1000 md, porosity = 0.2)
- Porosity = 1.0, homogeneous
- Effect of using different relative permeabilities – impact of using linear relative permeabilities
- Heterogeneous; absolute permeability is 1000 md in one direction and 100 md in the other direction
- Random permeability fields
- Different well locations

Results: Base-Case





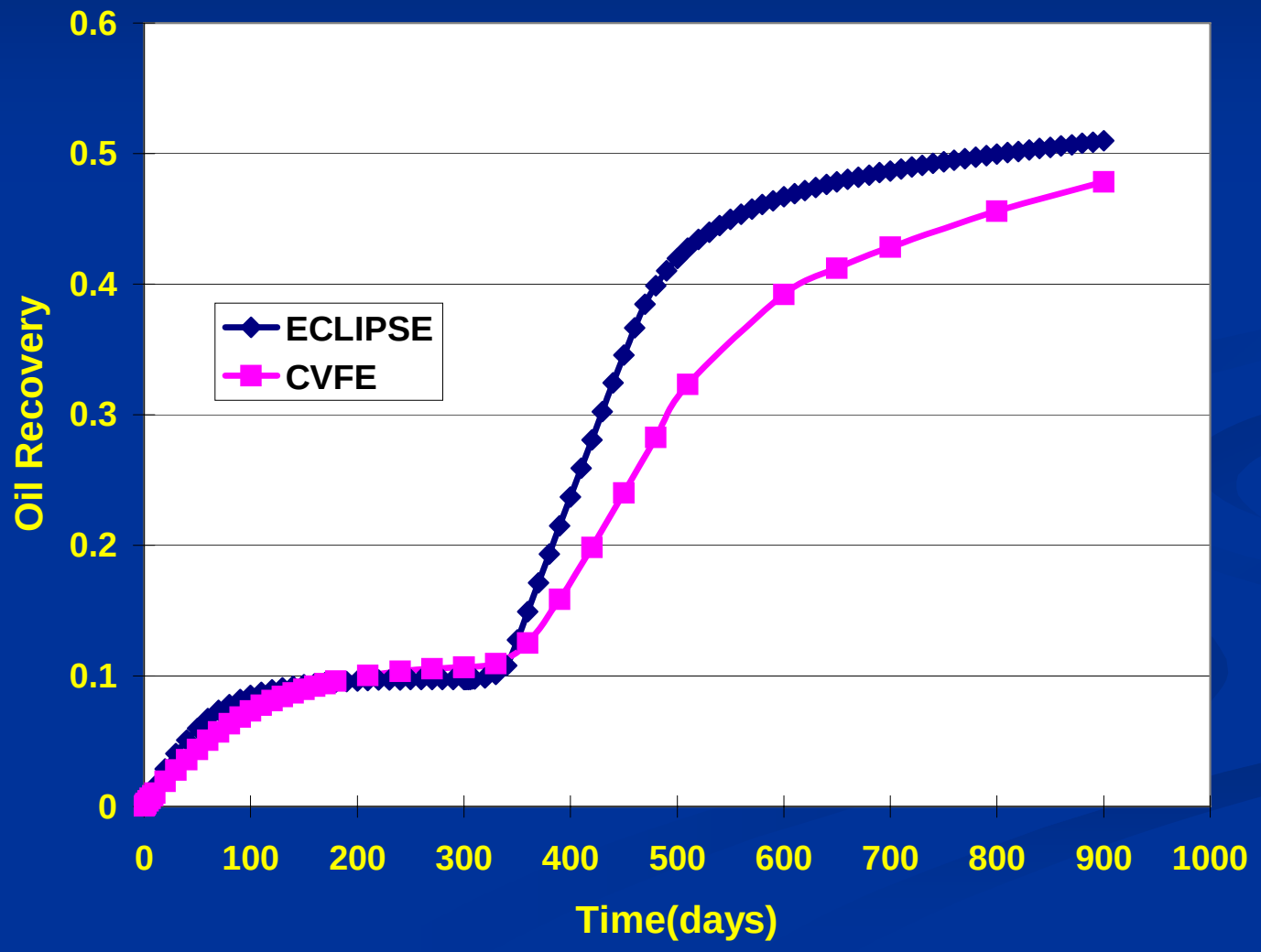
- Gas saturation at 300 days
- End of primary production

- Water saturation at 900 days
- Waterflood duration = 600 days
- Oil trapping observed

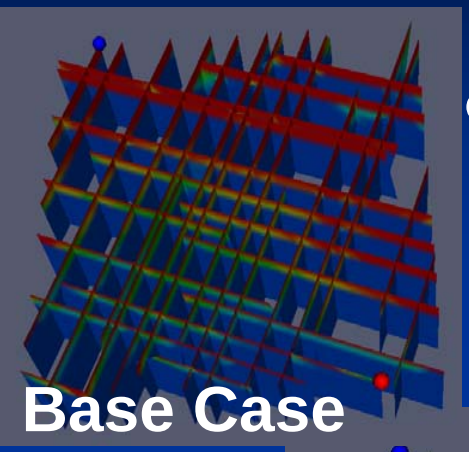
Comparison with Single Porosity Models

- Eclipse Simulator
- 50 x 50 x 5
- Only fracture blocks active
- Two sets of fractures, 17 in each direction
- Fully penetrating and extending over the entire domain
- Identical pore volume and OOIP
- Identical k*w
- All other parameters the same

Production Curve Comparison



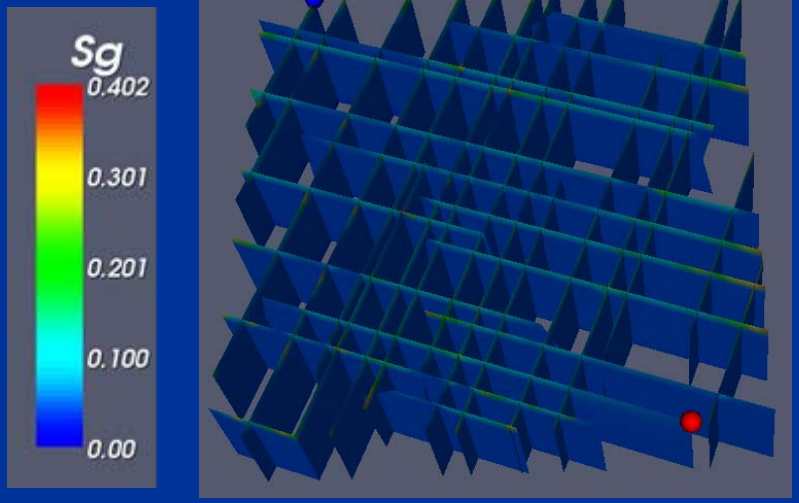
Increase porosity from 0.2 to 1.0
(OOIP five times the original value)



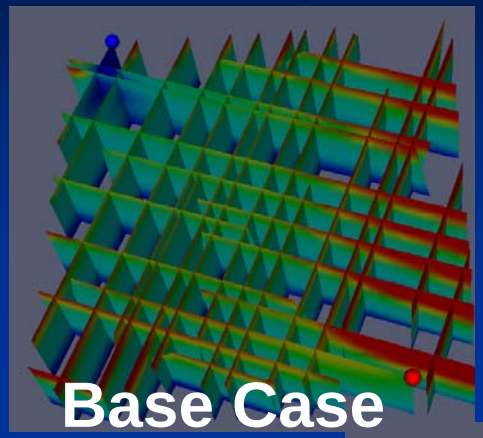
$\Phi = 0.2$

Base Case

$\Phi = 1.0$



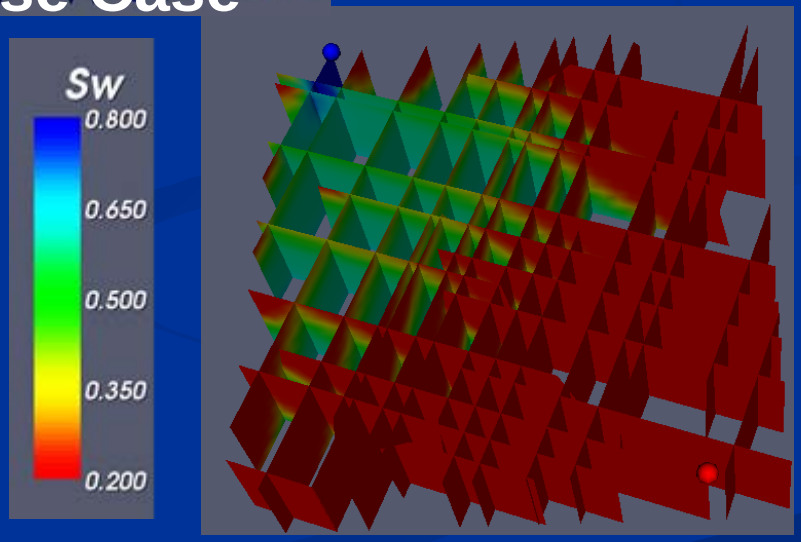
- Gas saturation at 300 days
- End of primary production
- Negligible gas evolution



$\Phi = 0.2$

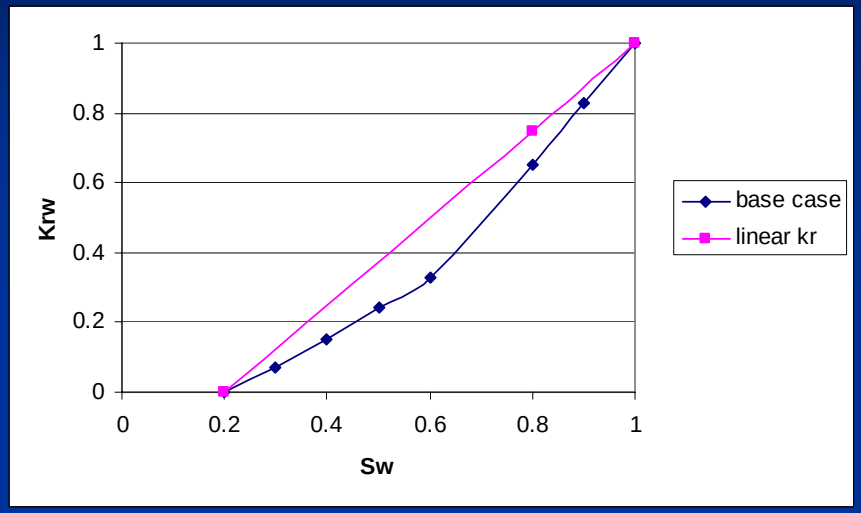
Base Case

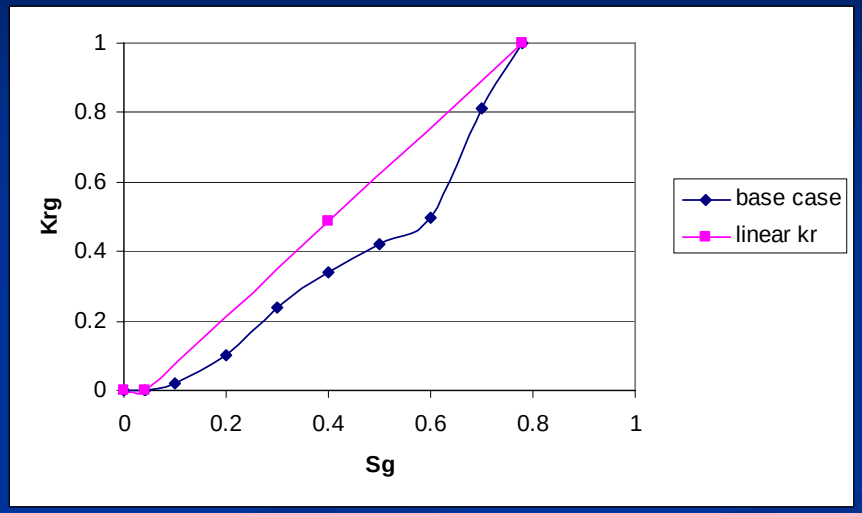
$\Phi = 1.0$

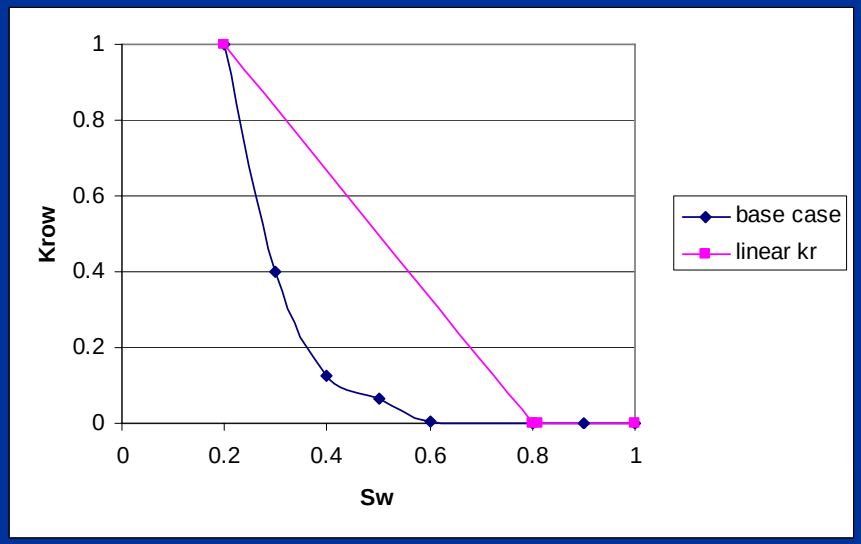


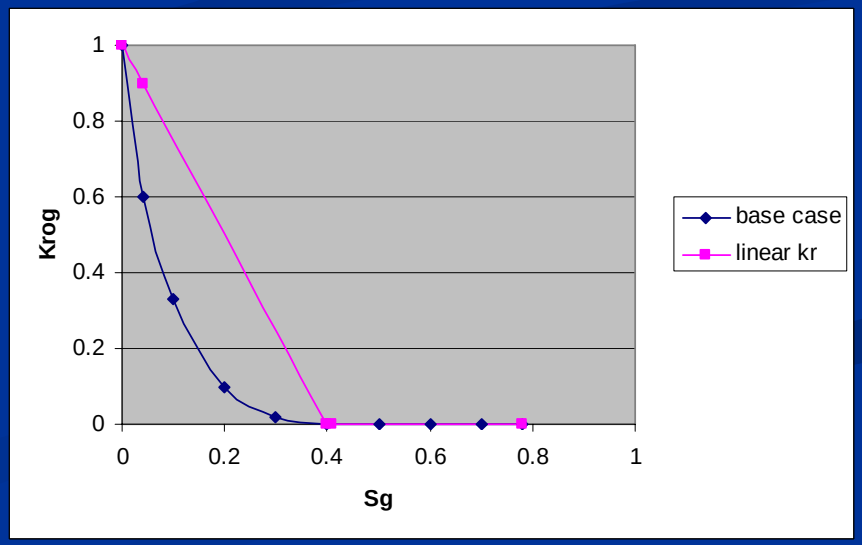
- Water saturation at 900 days
- Waterflood duration = 600 days
- More uniform waterflood
- Different flood dynamics

Modify Relative Permeability Curve

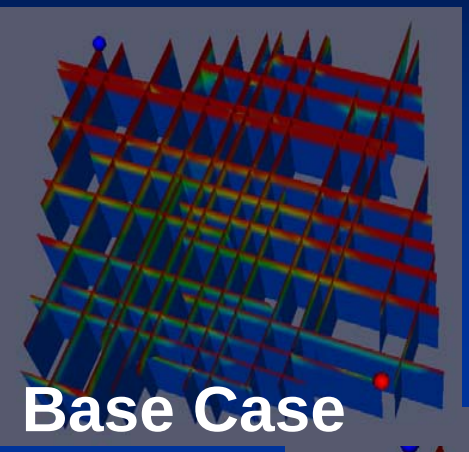




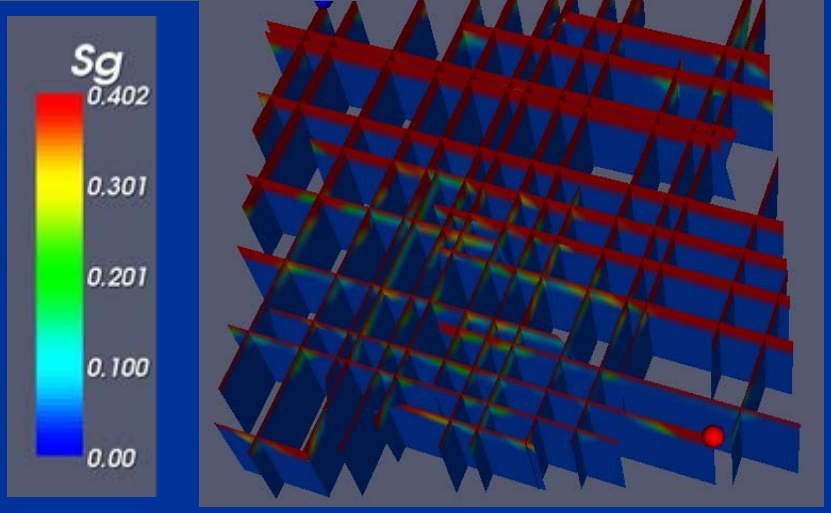




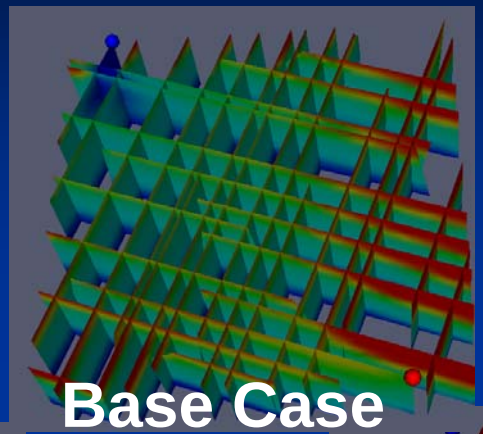
Modify Relative Permeability Curve



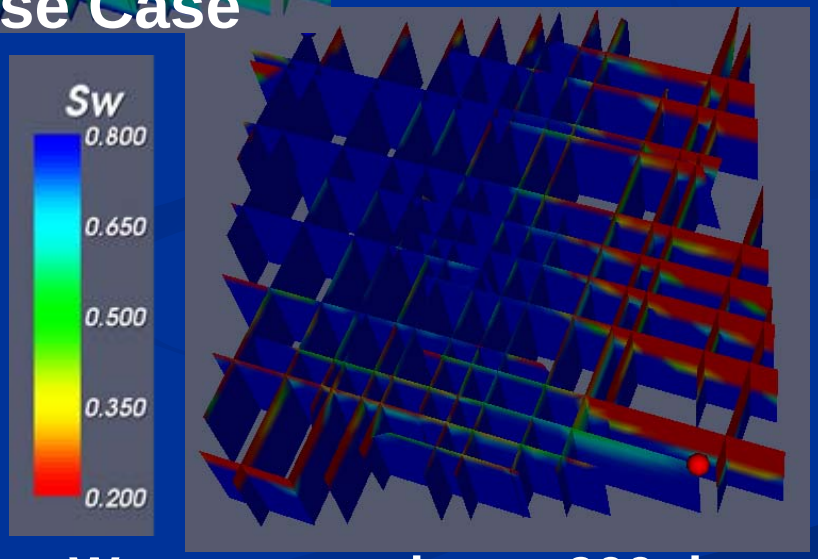
Base Case



- Gas saturation at 300 days
- End of primary production
- More gas evolution

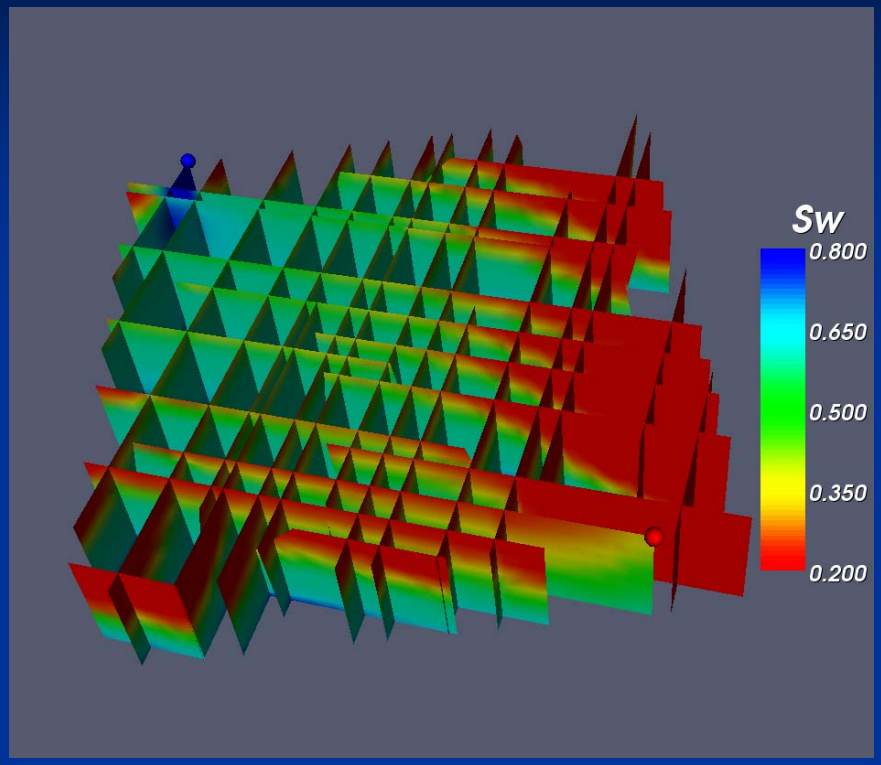


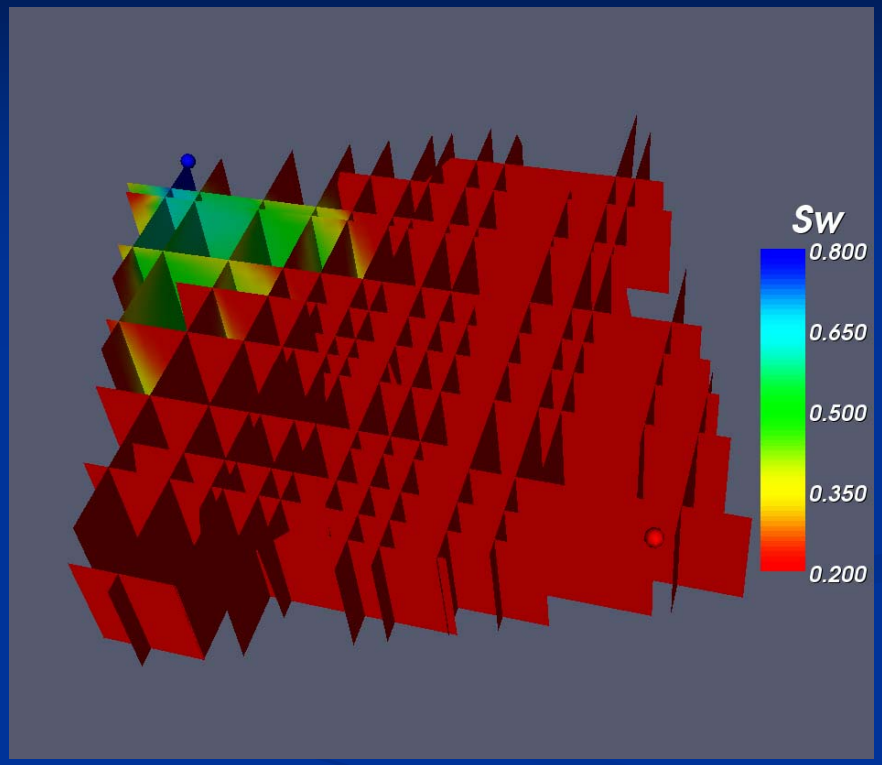
Base Case



- Water saturation at 900 days
- Waterflood duration = 600 days
- Higher oil recovery
- Oil trapping in different locations

Reduction in permeability to 100 md and 10 md

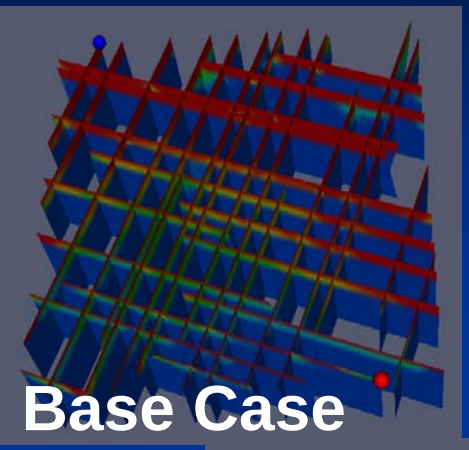




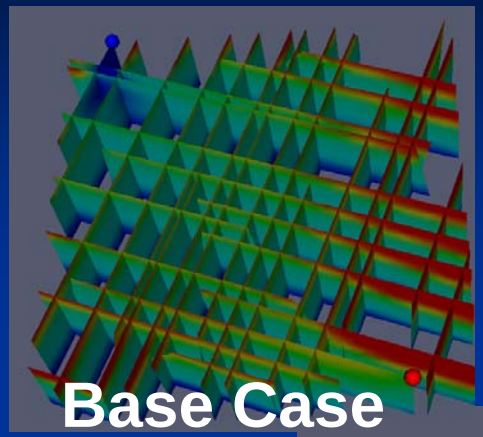
- 100 md permeability
- Water saturation at 4000 days

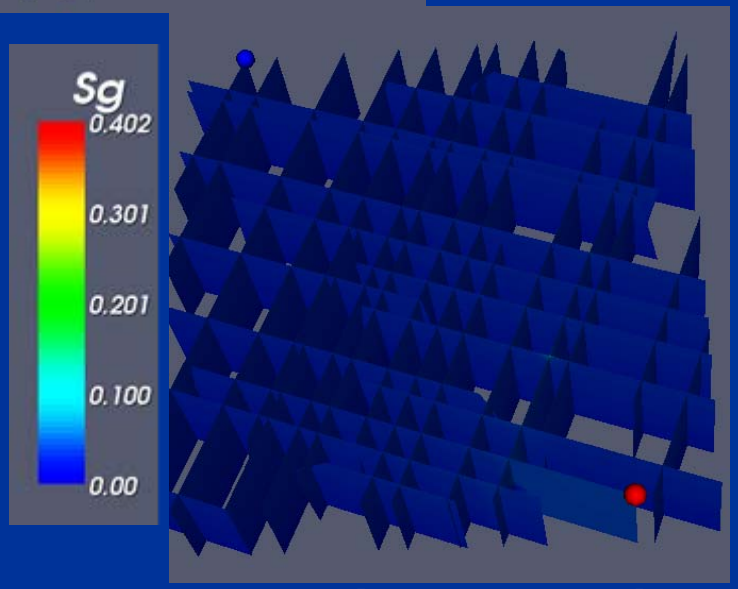
- 10 md permeability
- Water saturation at 4000 days

Reduce *k* from 1000 to 100 md in E-W Features

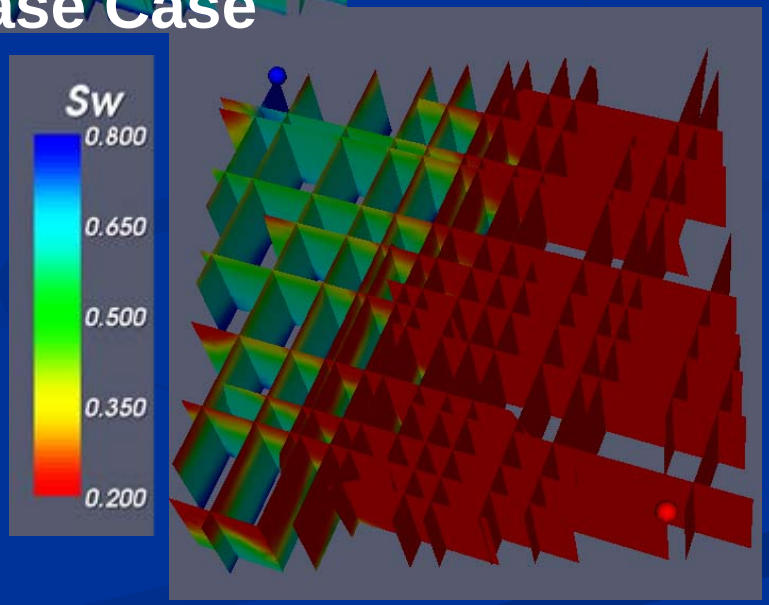


1000 / *k* (md) / 1000





1000 / *k* (md) / 100

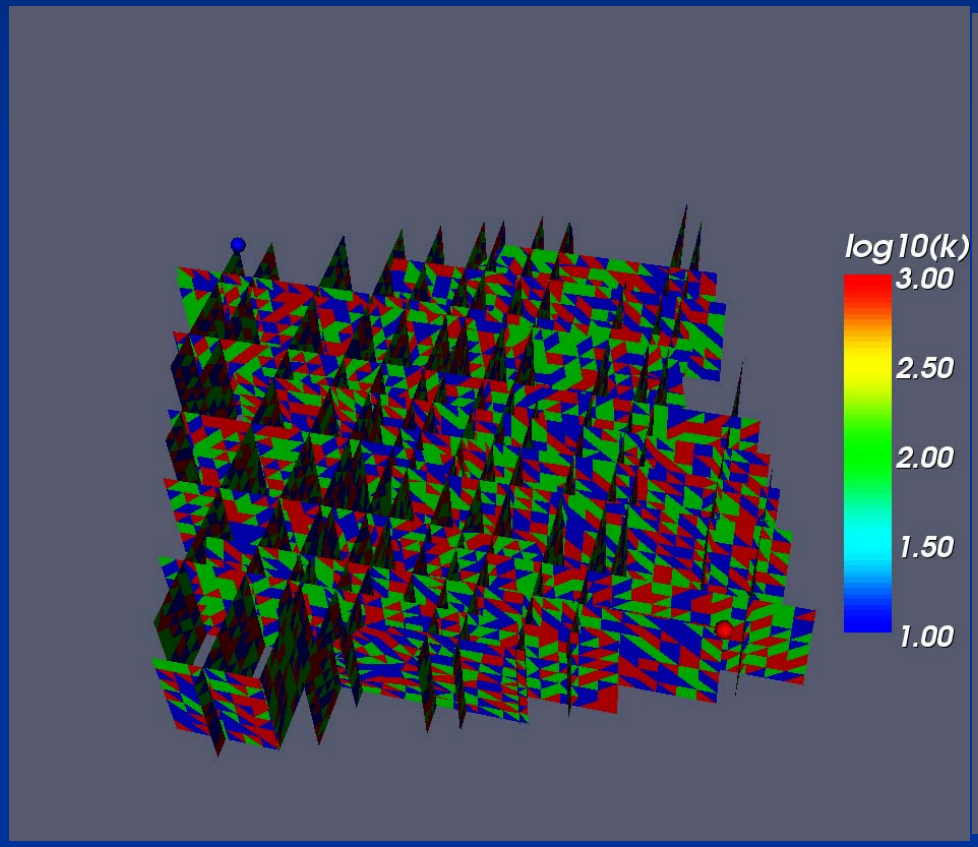


- Gas saturation at 300 days
- Negligible gas evolution

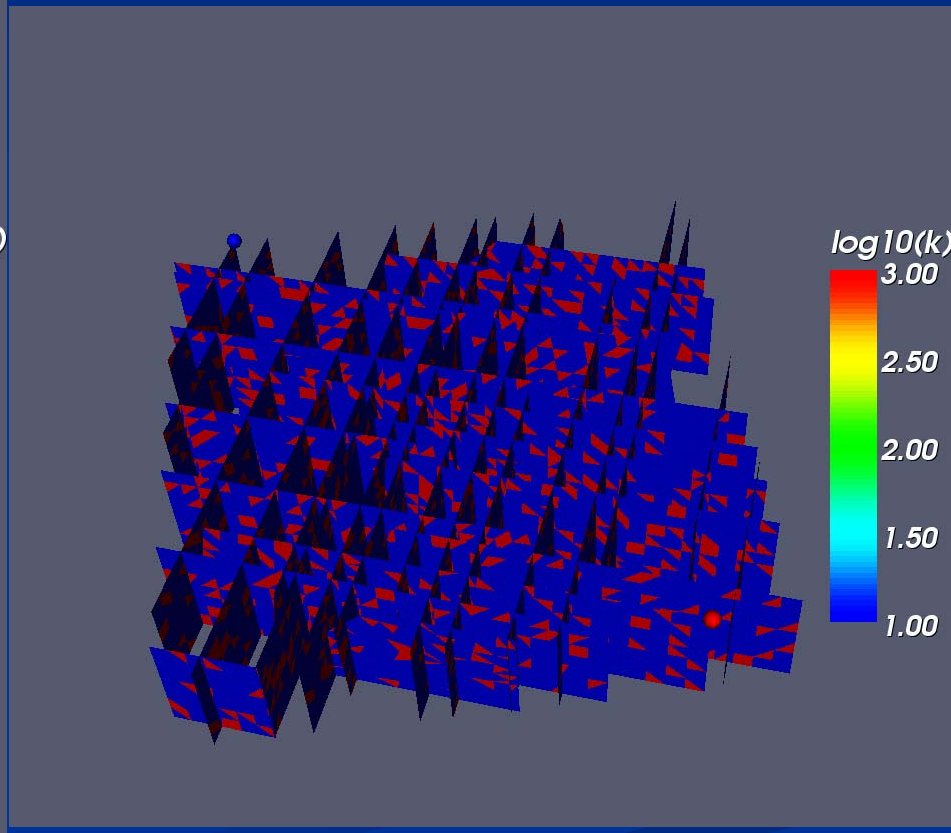
- Water saturation at 900 days
- Much lower oil production
- Lower permeability features control progress of the waterflood

Permeability Fields Used

1/3 of low, medium and high



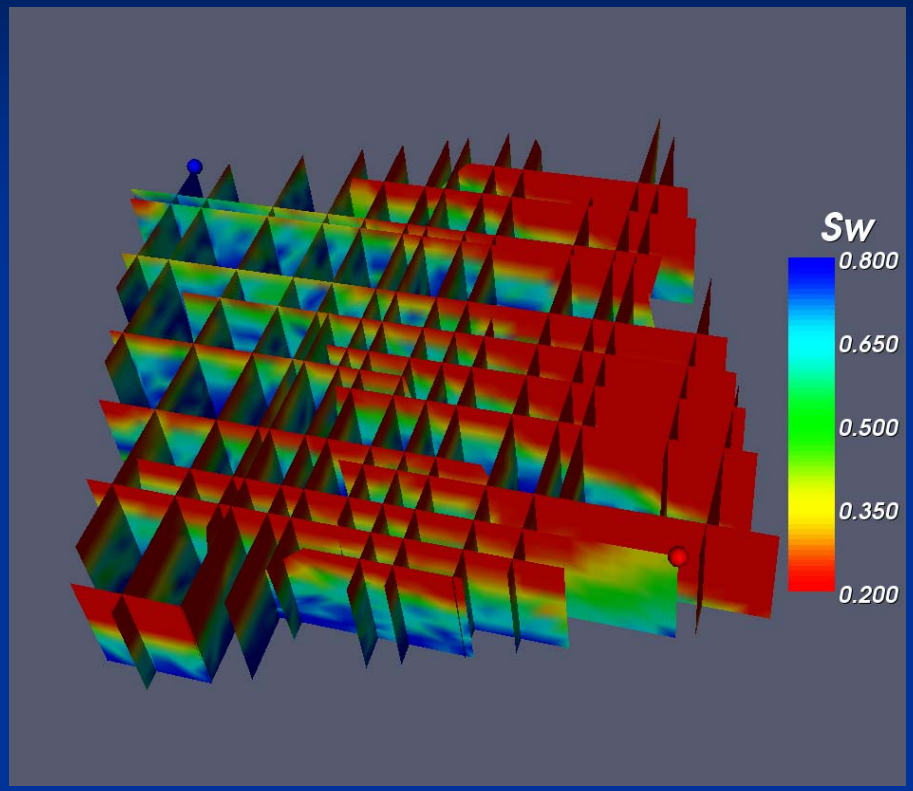
80% low, 20% high

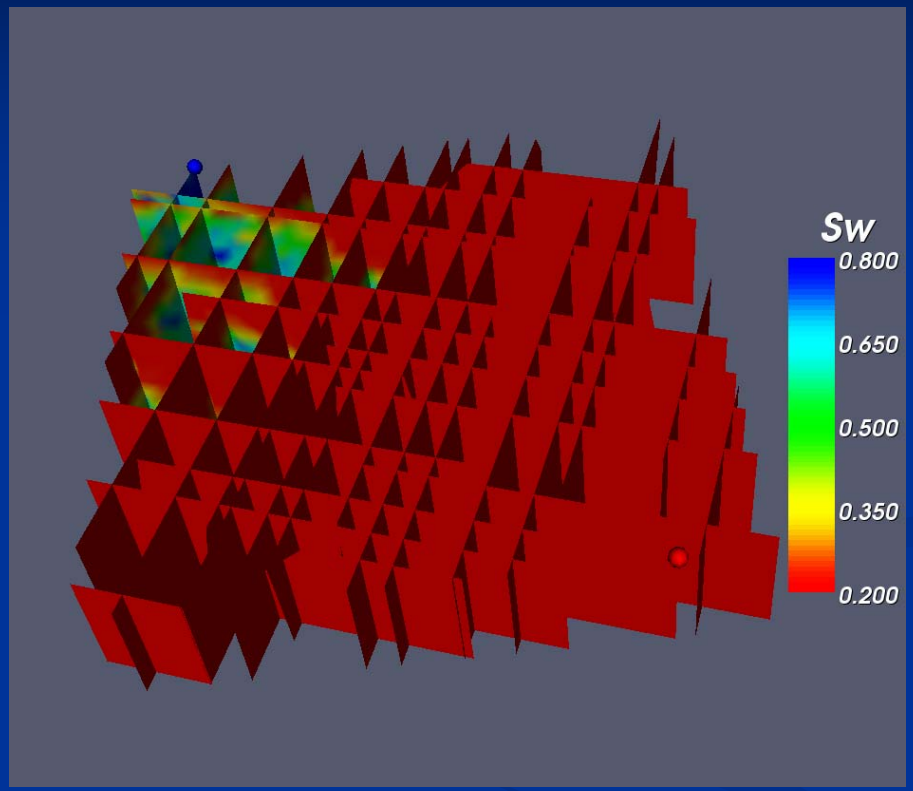


Low: 10 md

Medium: 100 md, High: 1000 md

Using Randomly Generated Permeability Fields





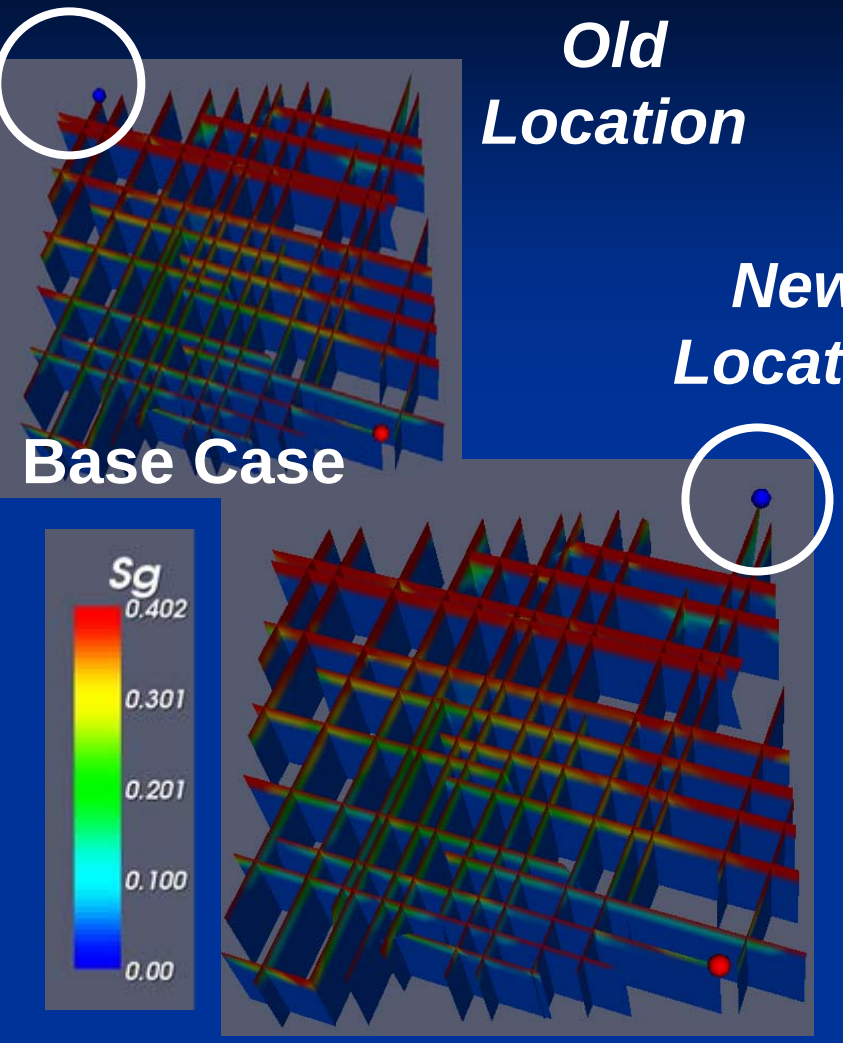
- Equal (1/3)distribution of 10, 100 1000 md
- Water pathways through heterogeneous features visible

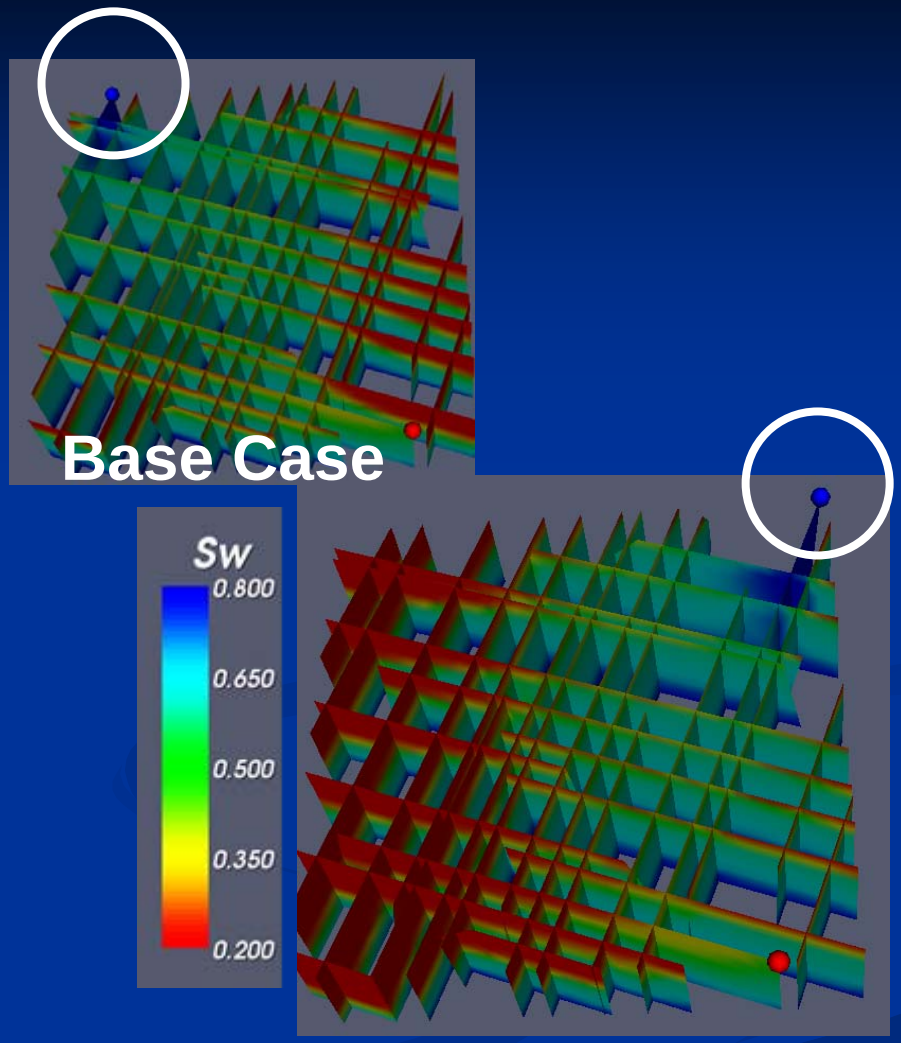
- 10 md – 80%; 1000 md – 20%
- Low oil production
- Lower permeability features control progress of the waterflood

Change Injection Well Location

Old Location

New Location

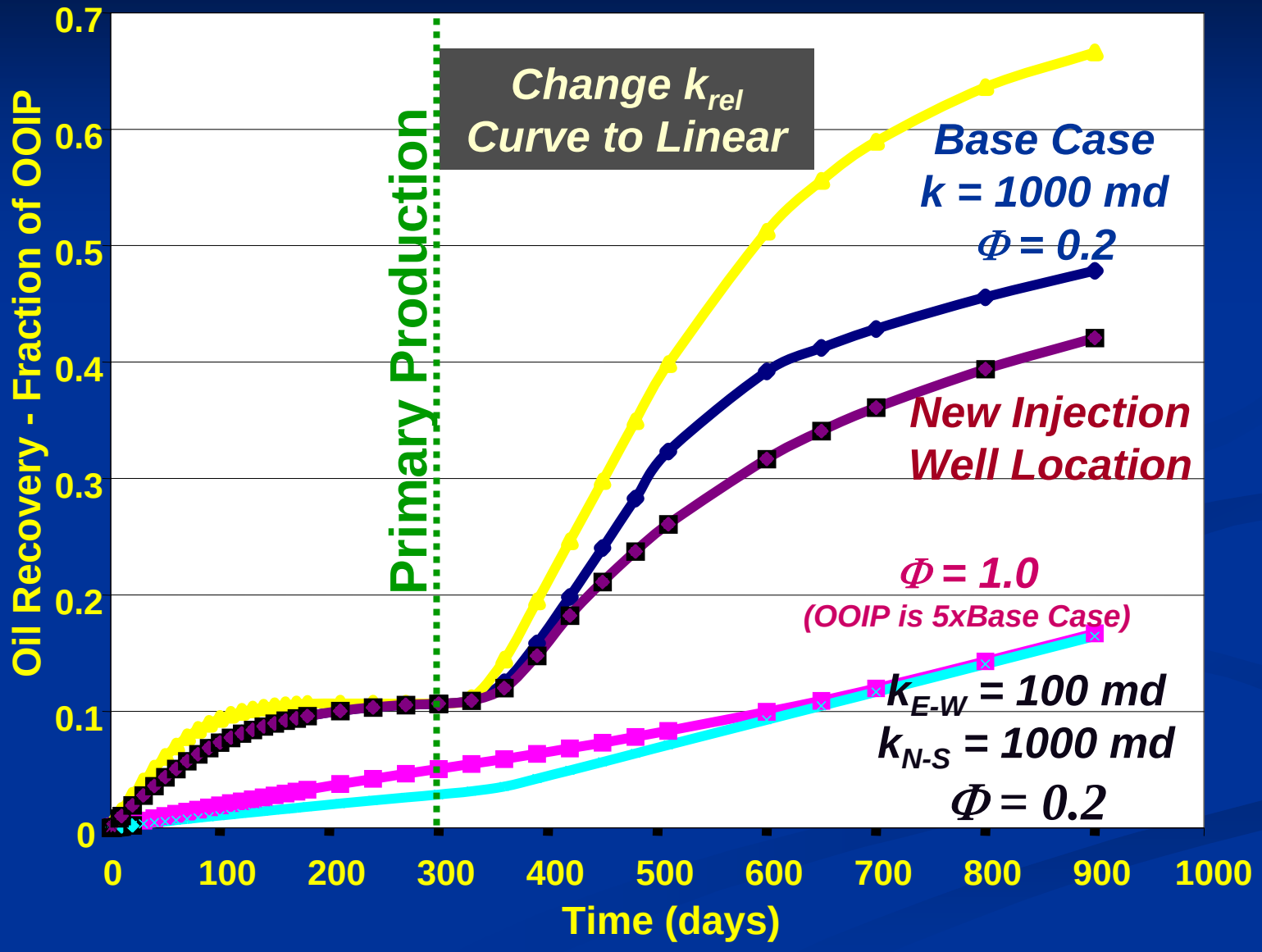




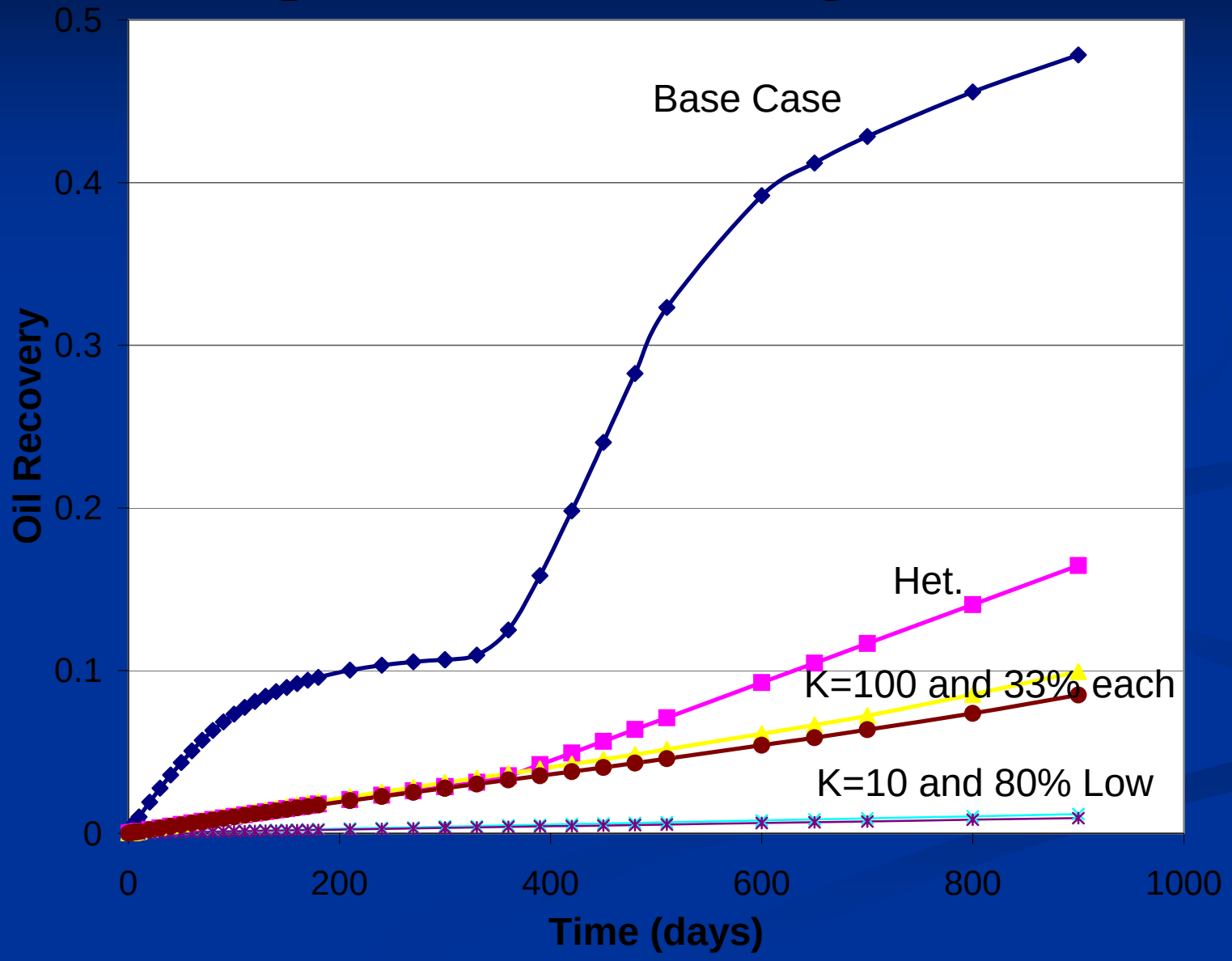
- Gas saturation at 300 days
- Similar to Base Case

- Water saturation at 900 days
- Nature and amount of oil trapping is different

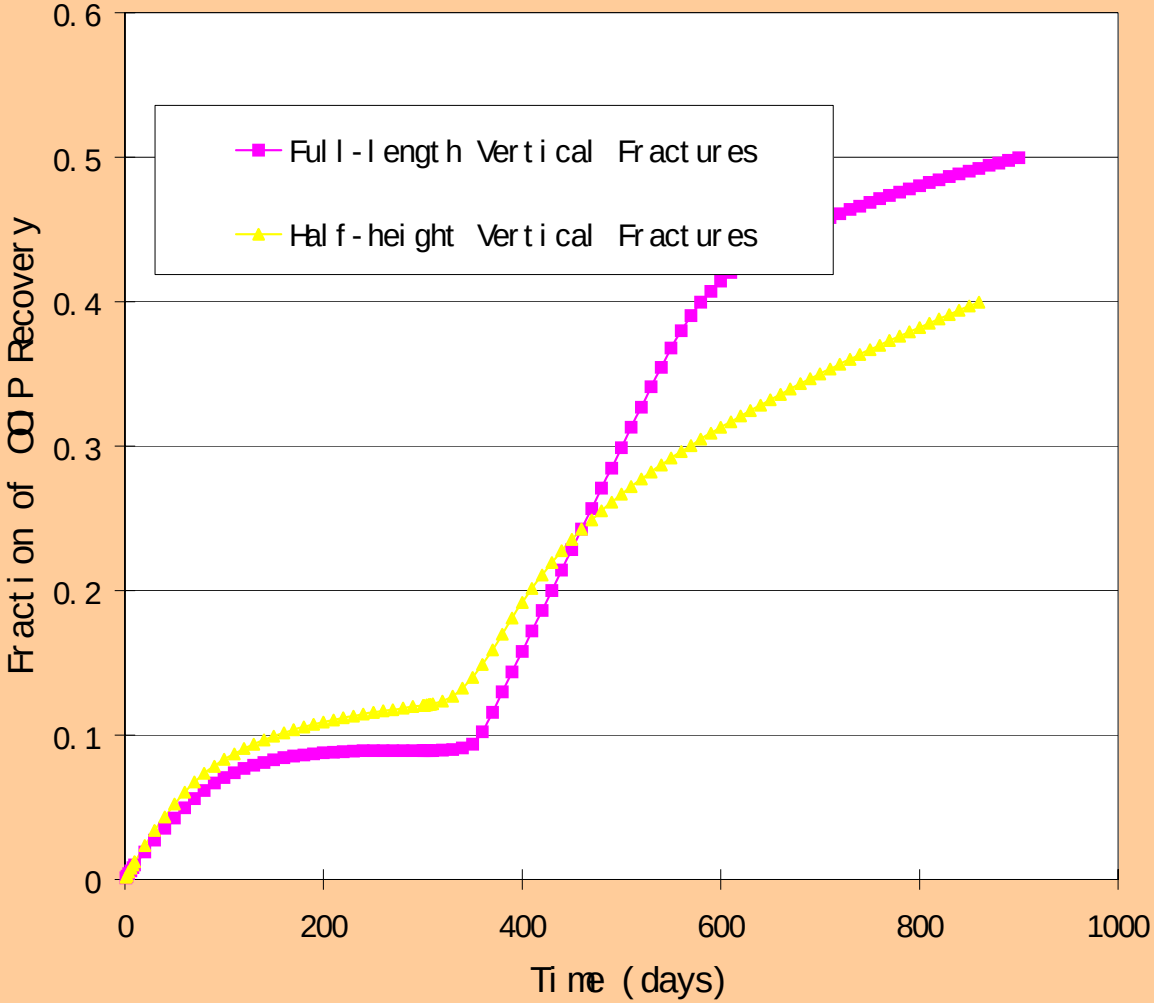
Oil Recovery Plots



Impact of other heterogeneities



Fracture Characteristics are Important



Summary

- A new three-dimensional, three-phase black-oil simulator based on the control-volume finite-element formulation is developed.
- Results from the simulator are in good agreement with results from Eclipse.
- Feasibility of performing three-phase simulations in complex, faulted/fractured domains demonstrated.
- Other case studies, with tilted, partially penetrating faults, which would be difficult to represent in finite-difference formulations are presented to demonstrate the applicability of the simulator.

Mixed Finite Volume Simulator

- Most appropriate for highly heterogeneous domains
  - Illustrated applications
    - Complex geometry – heterogeneity
    - Complex wells
  - Demonstration of coupling between physical and numerical models
    - Thermal simulator for complex domains ready
    - Compositional simulator will be ready in Summer 2006

MFE Equations

Mass balance equation:

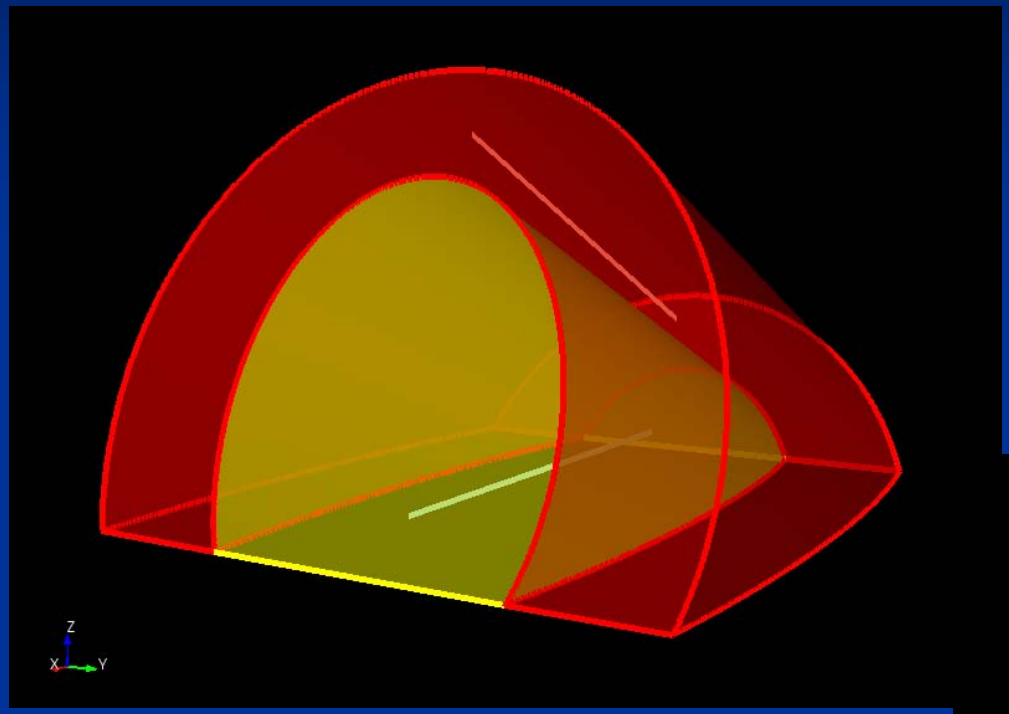
$$\sum_{i=0}^{2} \underline{u}_i \cdot \underline{n}_i \, A_i + V \left[\left(\phi \frac{S}{B} \right)^{t+1} - \left(\phi \frac{S}{B} \right)^{t} + q \right] = 0$$

Flux equation:

$$\text{LHS} = f_0 \int_{\Omega^e} \underline{v}_i \cdot \underline{v}_0 \, dx + f_1 \int_{\Omega^e} \underline{v}_i \cdot \underline{v}_1 \, dx + f_2 \int_{\Omega^e} \underline{v}_i \cdot \underline{v}_2 \, dx$$

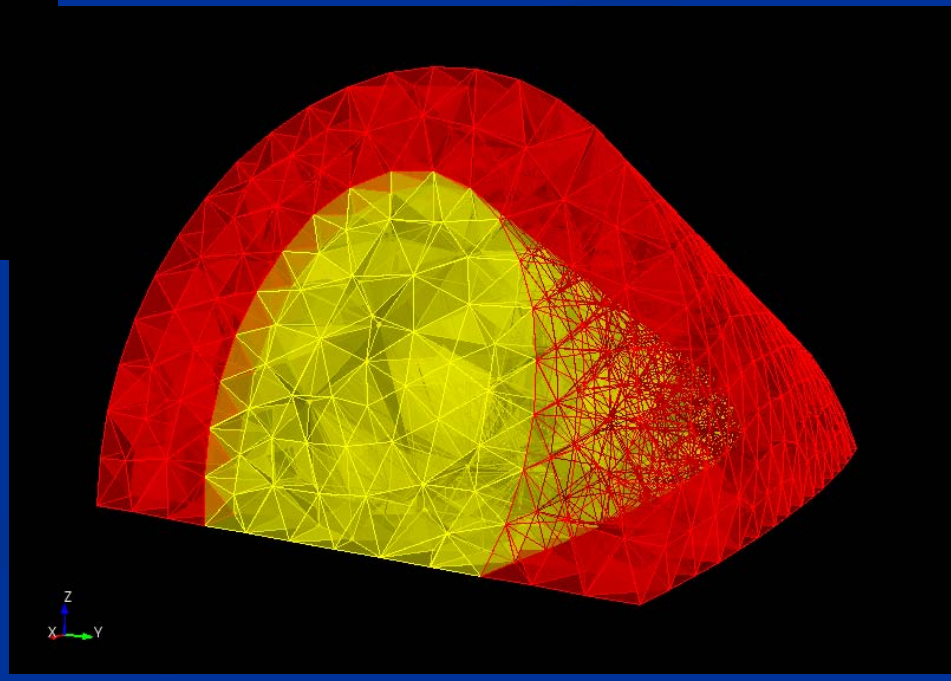
Let $v_{ij} = \int_{\Omega^e} \underline{v}_i \cdot \underline{v}_j \, dx$, then

Domain and Mesh Used in Thermal and Black-Oil Simulations

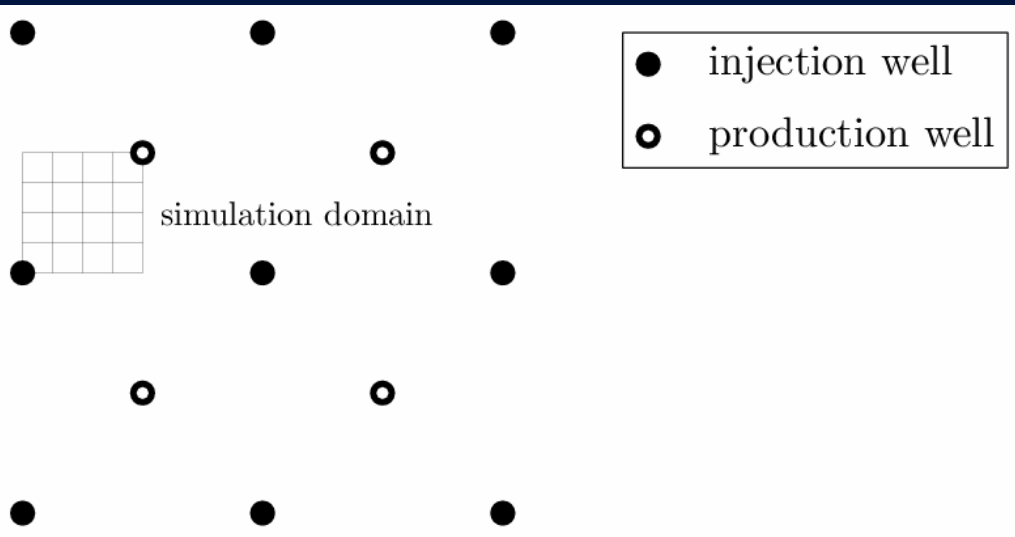


Domain consisting of outer and inner Cores of varying permeability

Meshing – Using CUBIT

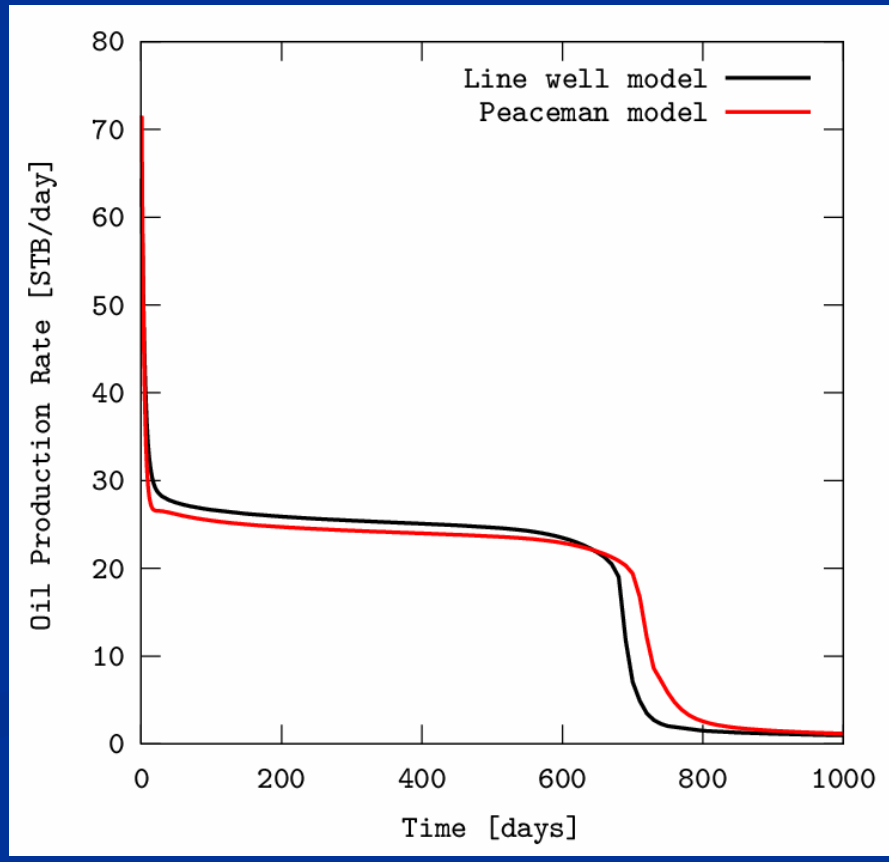


Well Model Validation

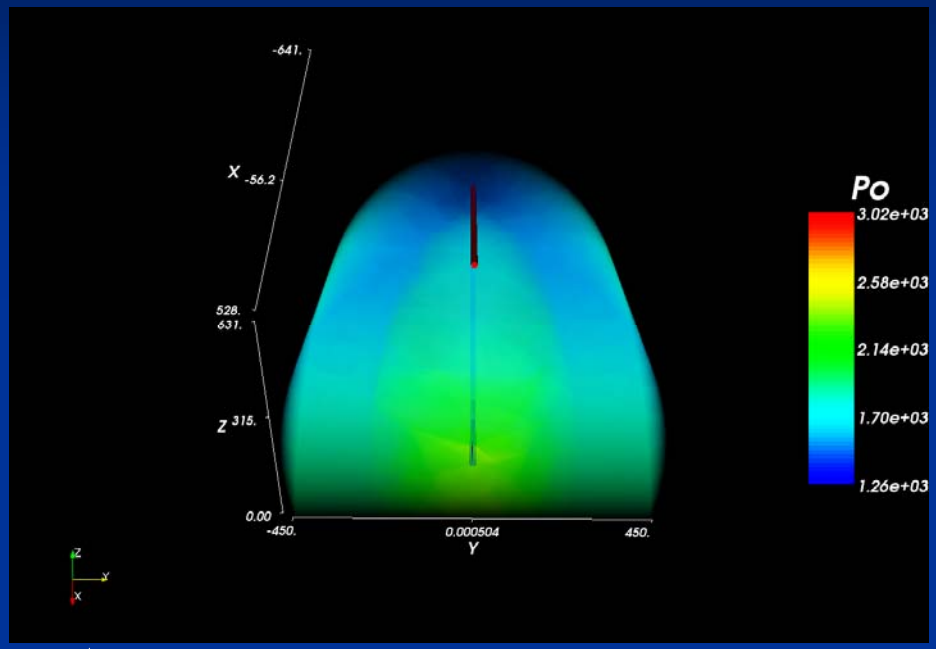


The pattern used for comparison

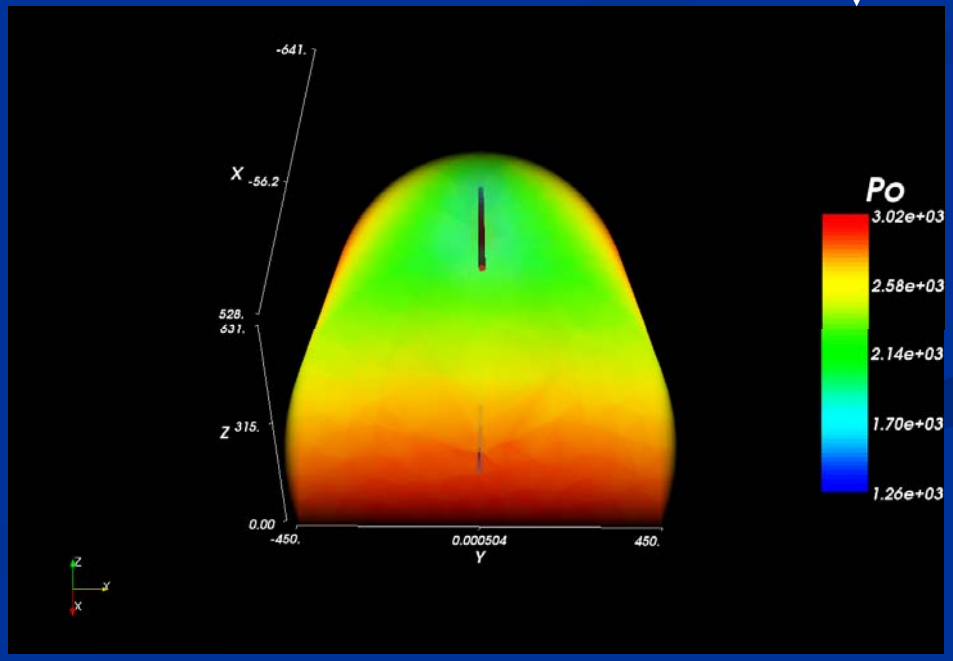
•Solutions for MFE with a new well model are compared to the results from Eclipse which uses the Peaceman Model



Pressure Profiles – Two different Scenarios

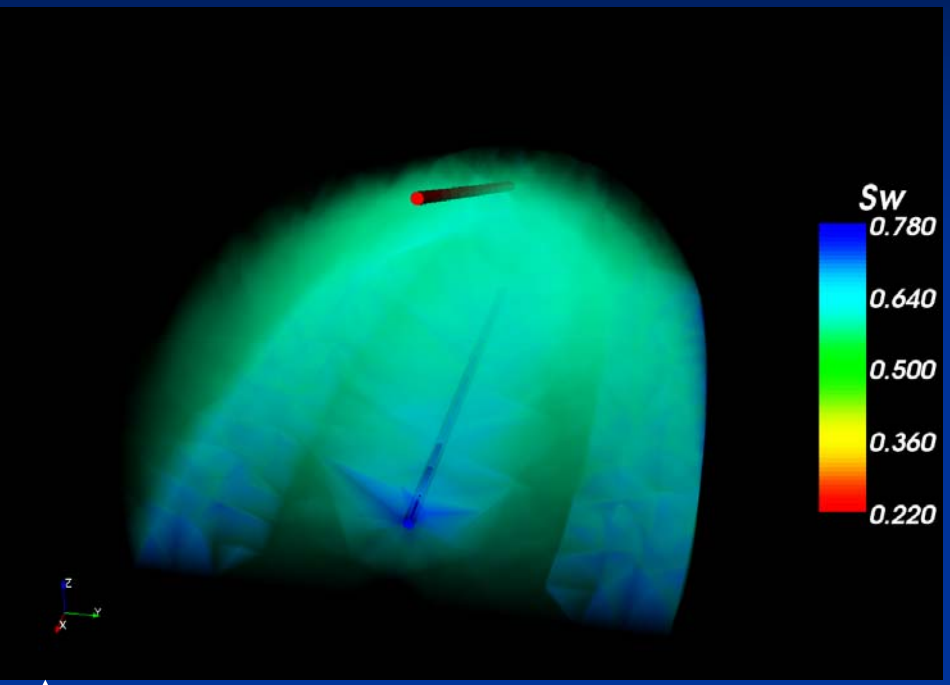


Higher permeability inner
Core channel water to
The production well
Preventing good sweep

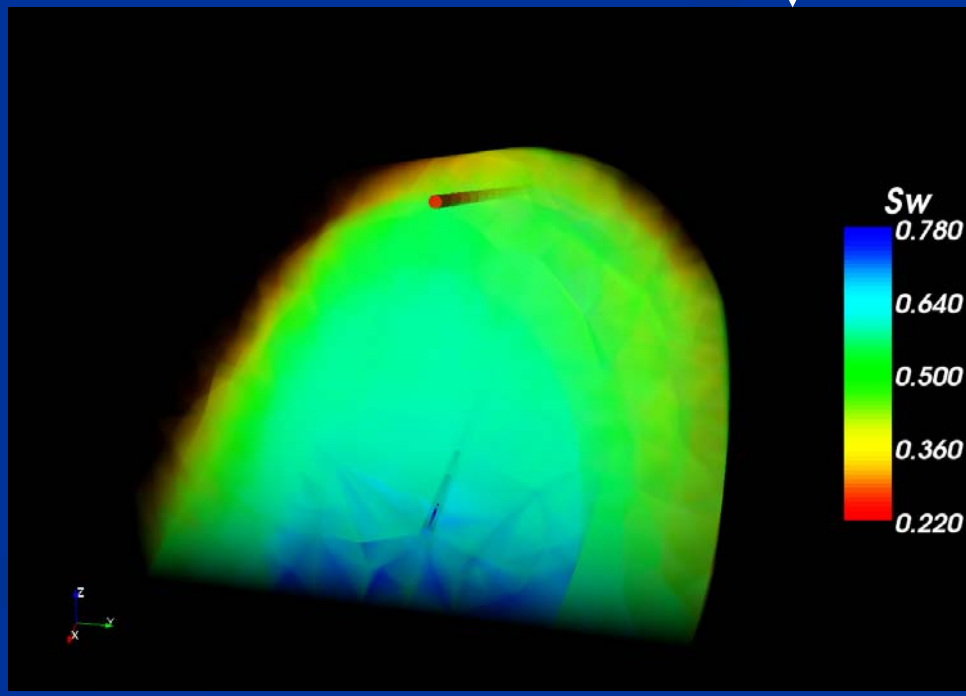


Lower permeability
Inner core affords
Encroachment of the
Outer layer and
Efficient sweep

Saturation Profiles – Two different Scenarios

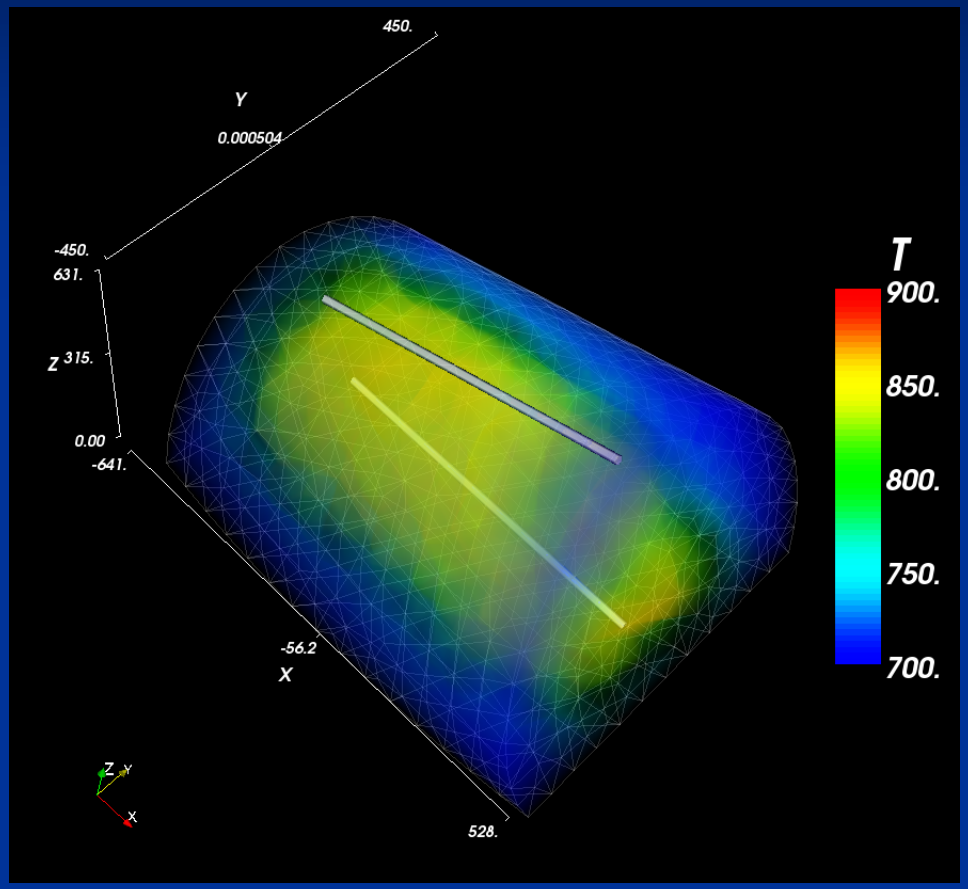


Higher permeability inner
Core channel water to
The production well
Preventing good sweep



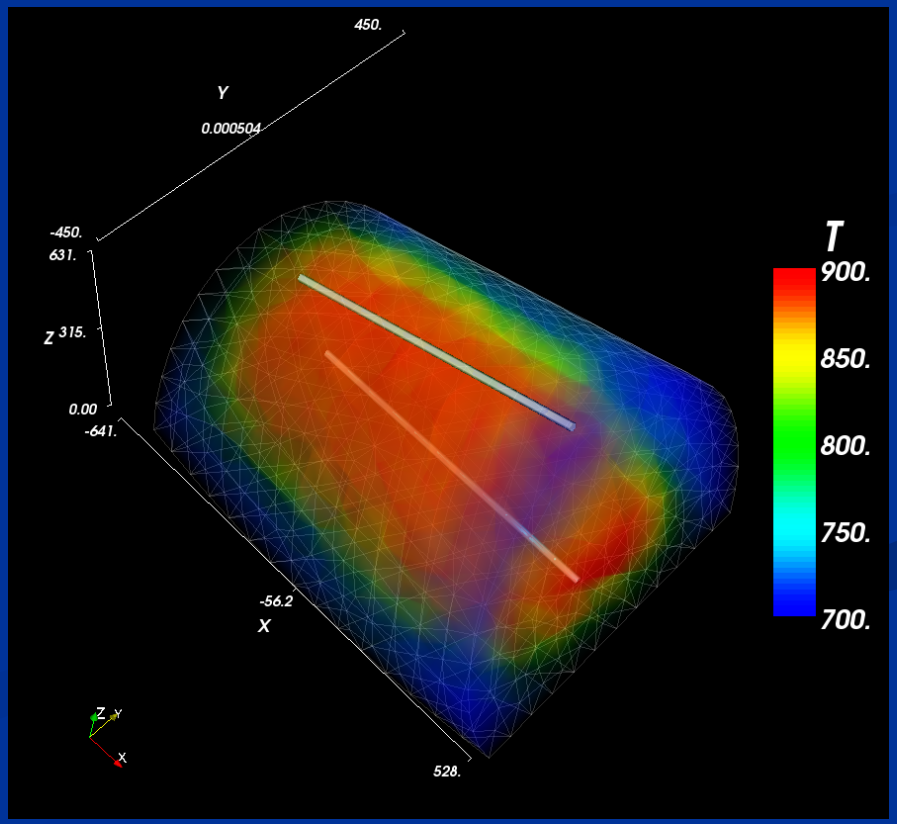
Lower permeability
Inner core affords
Encroachment of the
Outer layer and
Efficient sweep

Thermal Simulation - Temperatures

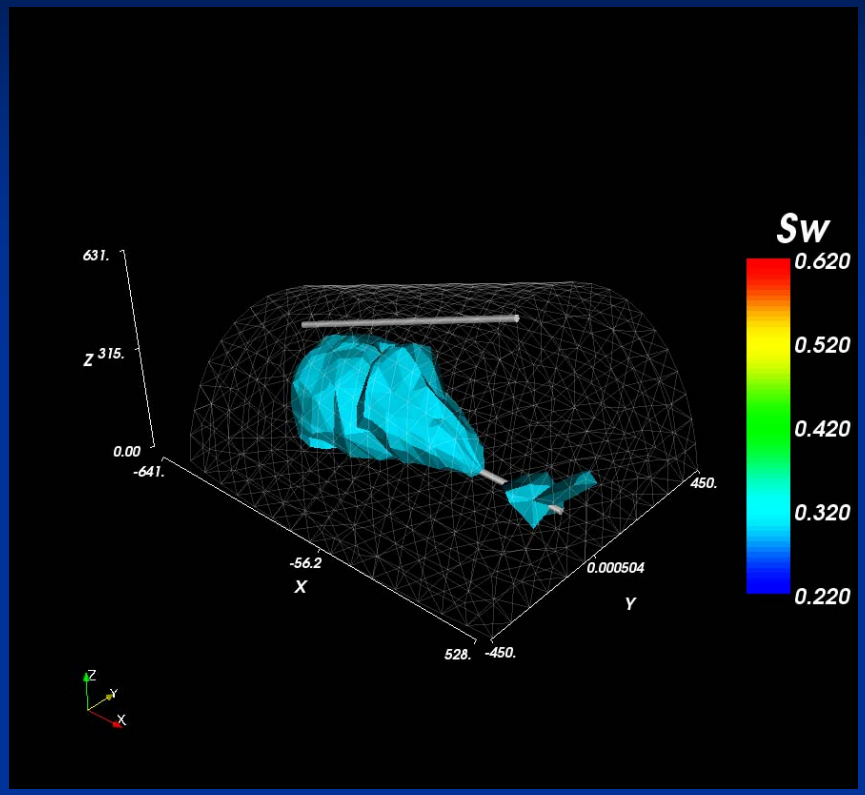


Lower Temperature

Higher Temperature

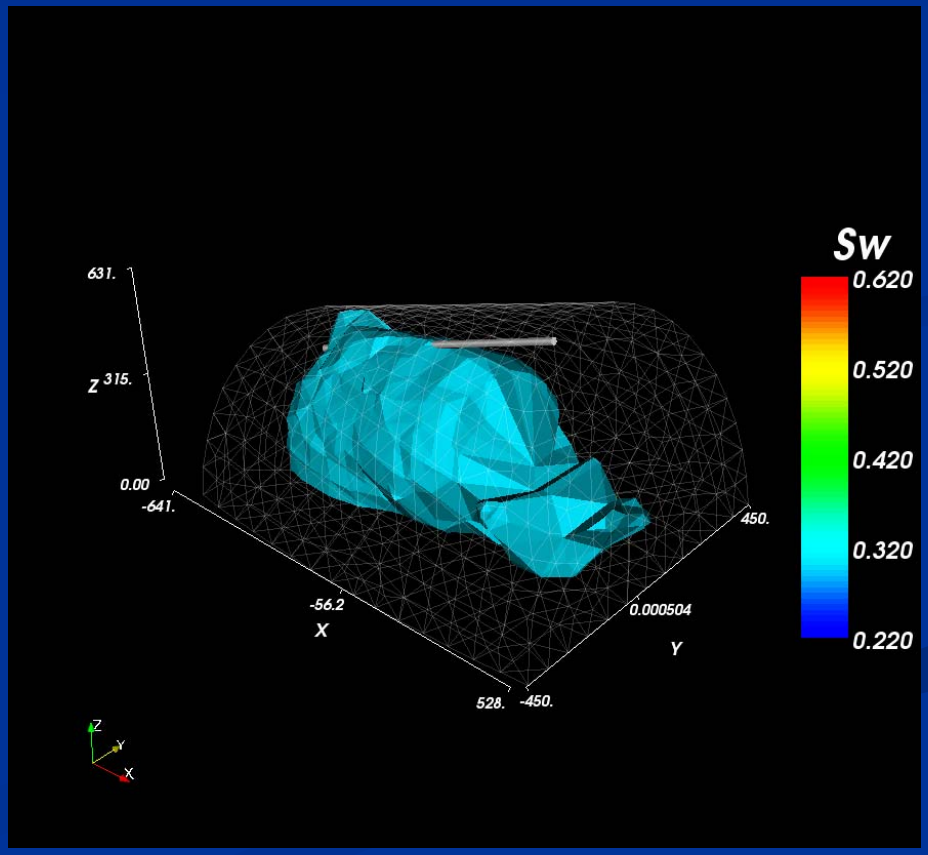


Thermal Simulation - Saturations



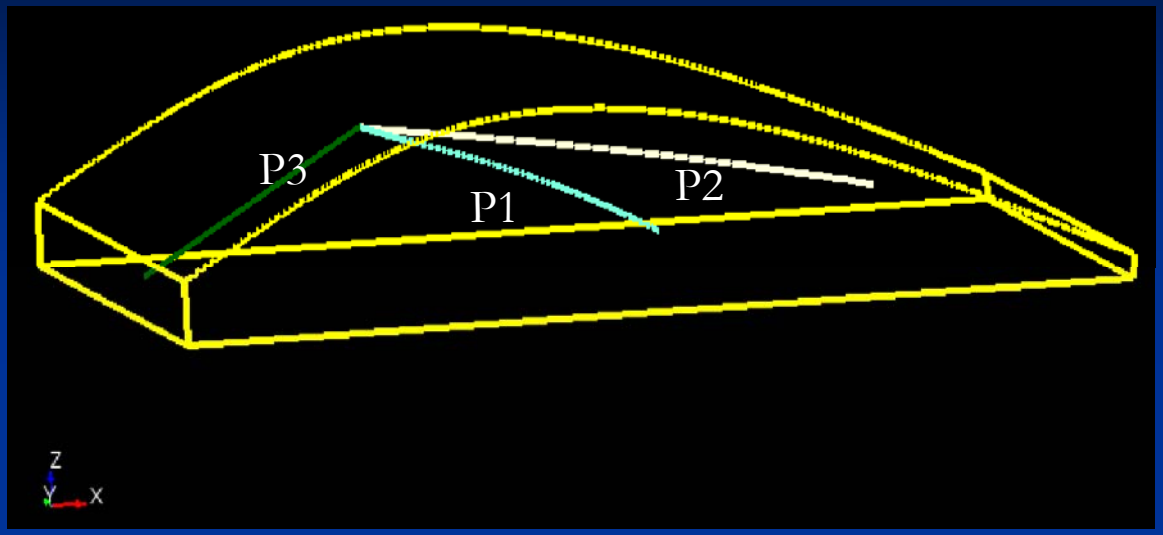
Low Temperature

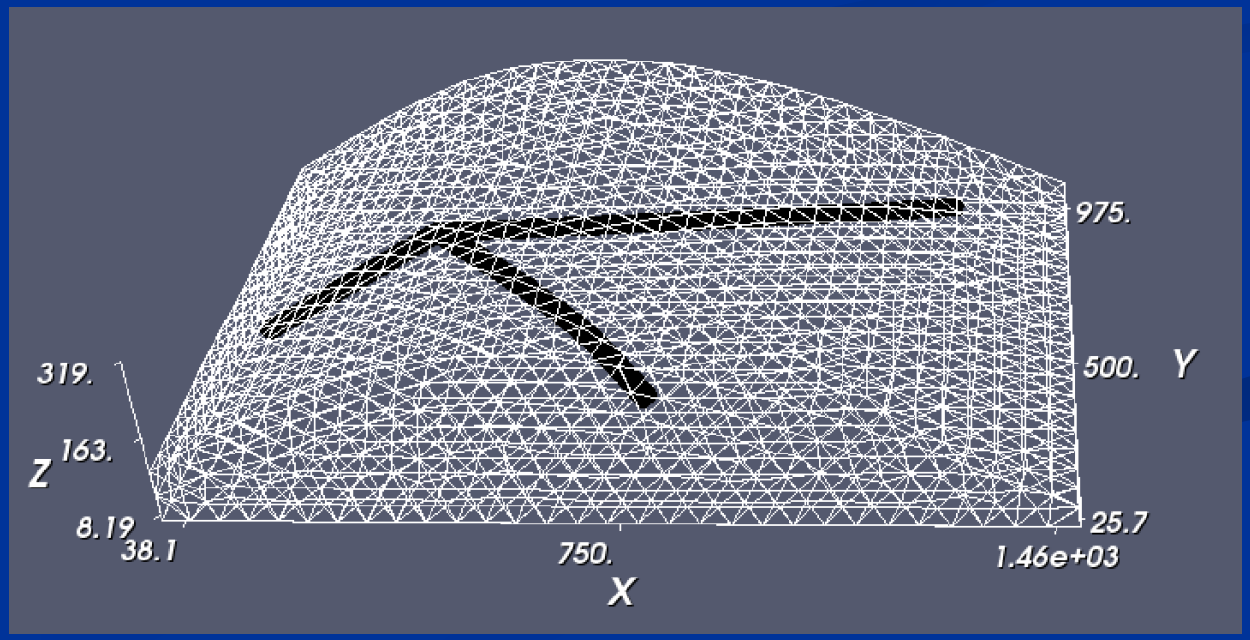
Higher Temperature



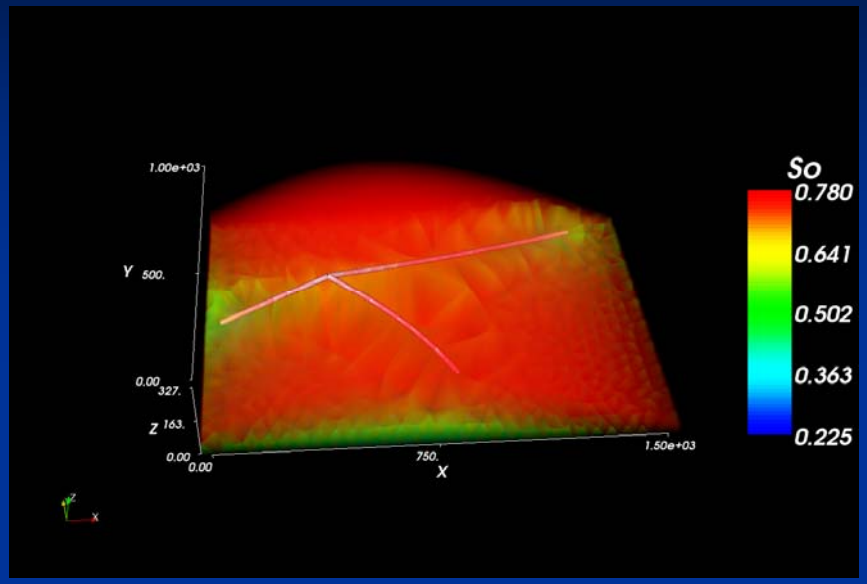
Constant saturation isosurfaces

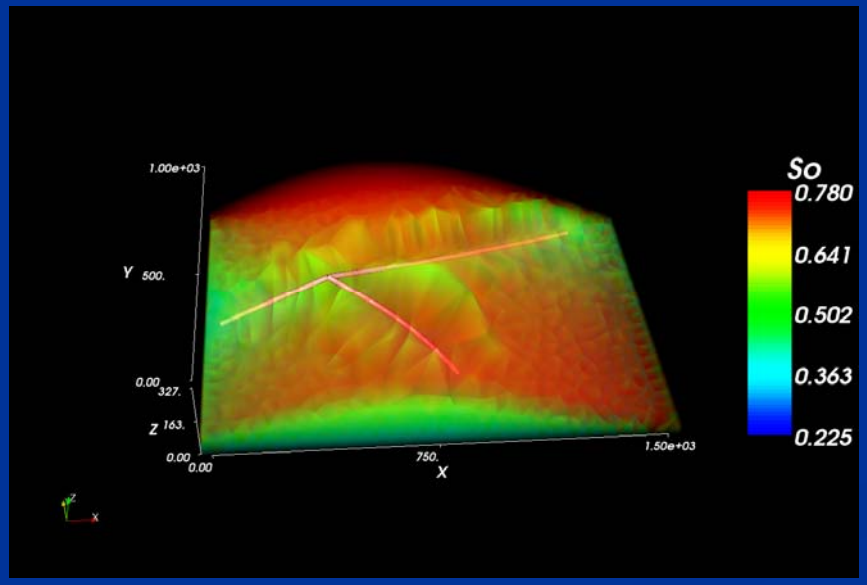
Domain and Mesh Used to Demonstrate the Capability of the Simulator for Multilaterals

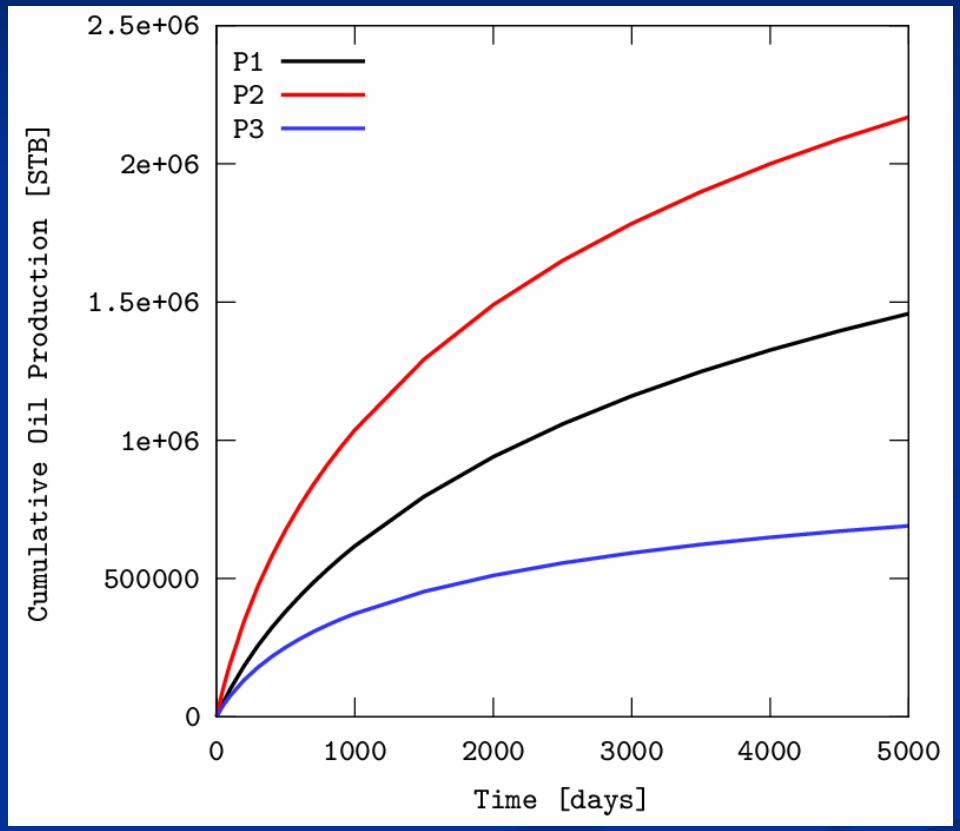




Simulations Using Multilaterals



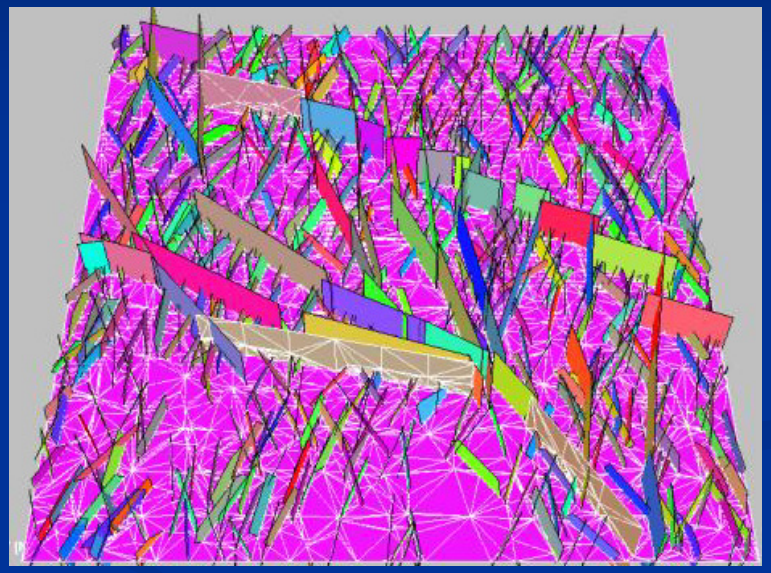




Primary production using a Dirichlet Condition (aquifer) at the bottom of the domain

Field-scale Simulations

- Hybrid Approach
  - Simulate "short" fractures or "fracture-swarms" using heterogeneous/anisotropic permeability field
  - Simulate "long" fractures using discrete-fracture approach – simulator described here



Major Accomplishments

- Decoupling of physical and numerical models allowing rapid simulator development
- Incorporation of the most modern solvers
- Direct compatibility with sophisticated fracture generation and meshing programs
- Three-phase finite element simulations of systems of complex geometry
- Two distinct numerical algorithms appropriate for specific applications – CVFE and MFV
- Benchmarked well models – allowing simulation of complex multilateral wells in complicated geometry
- Benchmarked hydraulic fracture simulations using compressible single-phase flow analytical results
- Thermal simulation of complex geologic fractured systems with complex wells now possible
- Parallel formalism for unstructured grids

Technology Transfer, 2005-06

- Regional workshop – Salt Lake City, March 2005
- SPE Reservoir Simulation Symposium – Paper and Poster
- Geological Society of America Meeting – Salt Lake City – Two Papers
- IOR Meeting – Paper and Poster

Other Members of the Team

- Jim Evans
- Craig Forster
- Yi-kun Yang
- Sriram Balasubramaniam
- Ganesh Balasubramaniam
- Yao Fu
- Kan Huang
- Zhiqiang Gu
- Huabing Wang