Geomechanical simulation of CO_2 leakage and cap rock remediation

DE-FE0001132

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

August 21-23, 2012

Presentation Outline

- Benefit to the program
- Project overview
- Technical status
- Accomplishments to date
- Summary

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Benefit to the Program

- Program goals being addressed.
  - Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones.
- Project benefits statement.
  - The project develops a coupled reservoir and geomechanical modeling approach to simulate cap rock leakage and simulate the success of remediation of leakage paths through the cap rock. This technology, when successfully demonstrated, contributes to the Carbon Storage Program's effort of ensuring 99 percent CO2 storage permanence in the injection zone(s).

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Project Overview: Goals and Objectives

The main objective for this project is to develop a novel approach to simulate cap rock leakage and simulate the success of remediation of leakage paths through the cap rock for shallow CO2 injection sites through coupled reservoir and geomechanical modeling. The specific objectives include:

I. develop a detailed 3D shared earth model, to use as a consistent data set for coupled reservoir and mechanical simulations.

II. develop methods to perform coupled 3D reservoir and multi scale geomechanical simulations using existing commercial software and conduct simulations on potential shallow sequestration sites in Missouri.

III. develop fracture leakage remediation methods for sealing fractures and faults if a leak through the cap rock occurs and develop modeling capabilities for evaluating success of fracture remediation.

Outline Technical Status

- Leakage risk from CO_2 sequestration sites
- Shallow sequestration in Missouri
- Evaluation of sealant materials
- Coupled simulations

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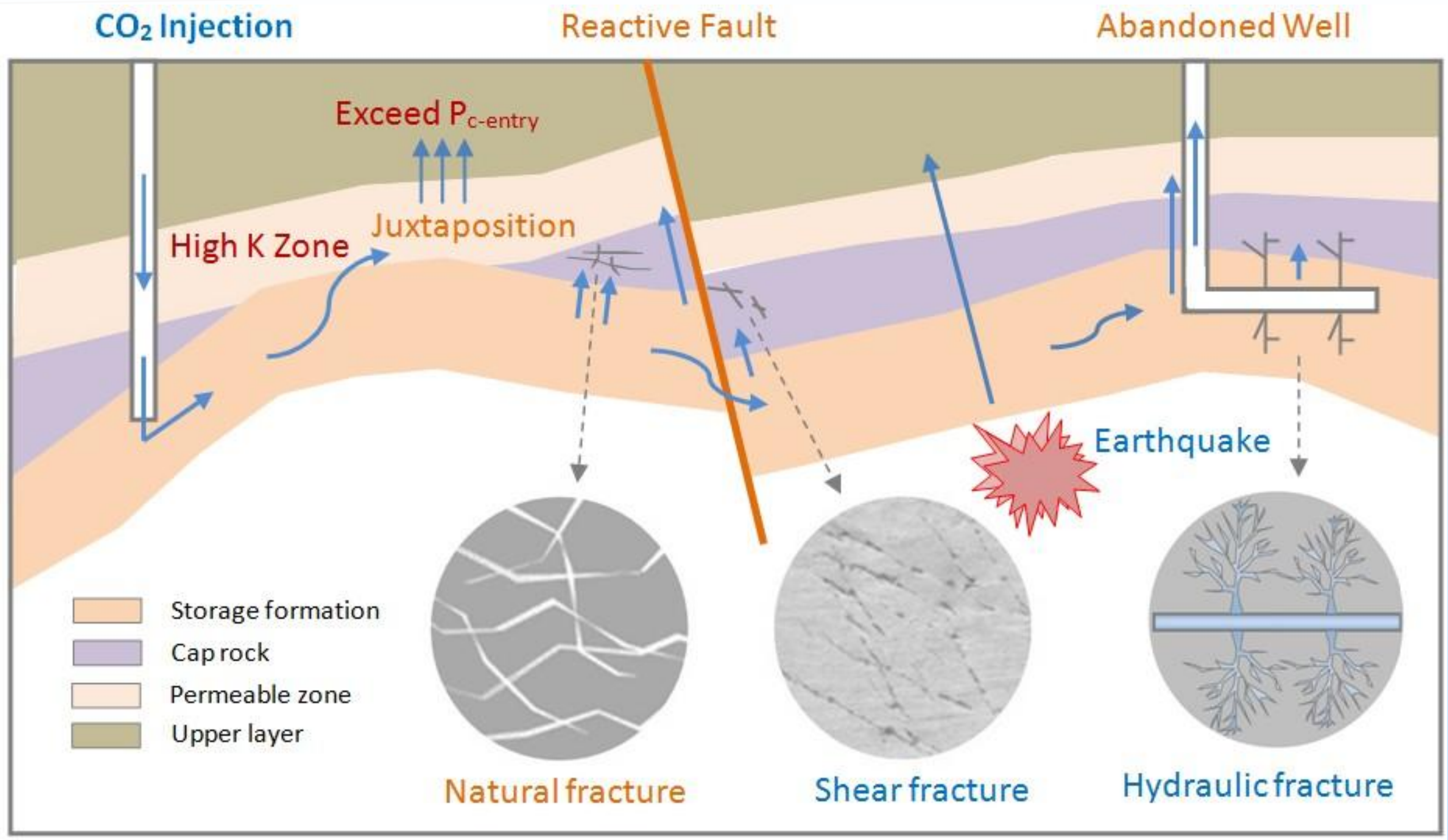
Leakage mechanisms



Matrix
- Capillary entry pressure
- Seal permeability
- Pressure seals
- High permeability zones

Structural
- Flow on faults
- Flow on fractures
- Flow between permeable zones due to juxtapositions

Geomechanics
- Hydraulic fracturing
- Creation of shear fractures
- Earth quake release

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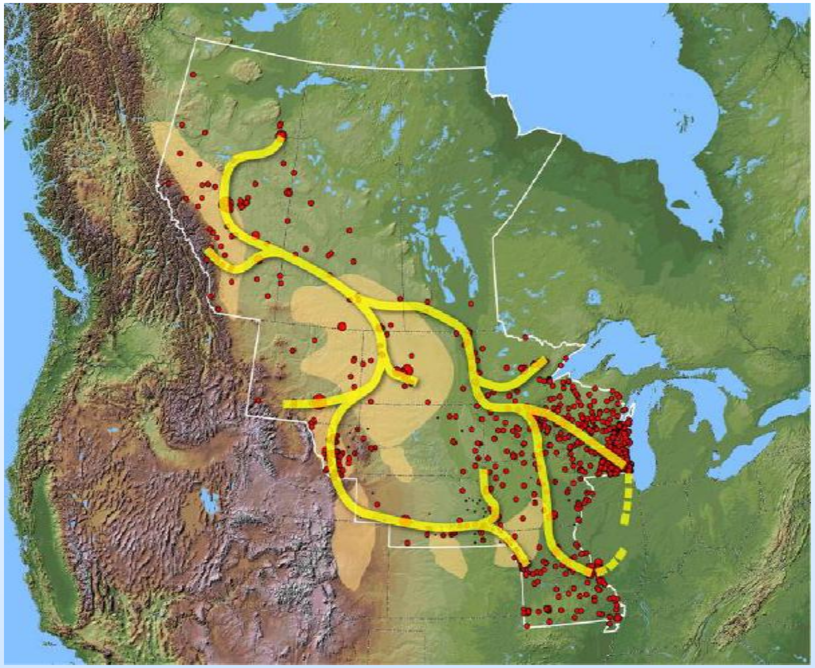
Why shallow sequestration?

The State of Missouri lies at the furthest point on the PCOR proposed transportation route and would likely be subject to the highest transportation costs.

City Utilities of Springfield was a partner in this project and provided data for their test pilot site.

City Utilities of Springfield (CU), along with other utility companies and with DOE funding investigated the feasibility of sequestering CO_2 at the CU Southwest Power Station, in Springfield, MO. *The Lamotte sandstone turned out to contain freshwater and this site is abandoned.*



Red is point sources of CO2 and with potential pipe lines for CO_2 transport in yellow.

Source, PCOR

Lamotte Sandstone Evaluation

Cap Rock Sequences

Reservoir Rock Sequences

Period	Lithology	Formation Name	Group	Rock Type	Max Thickness (m)
Lower Ordovician		Jefferson City	Ozark	Cherty/Drusy Dolomite	3050
		Roubidoux			
		Gasconade			
Upper Cambrian		Eminence			
		Potosi			
		Derby Doerun	St Francois Confining Unit	Shaly Dolomite	394
		Davis		Dolomite shale	510
		Bonneterre	St Francois	Dolomite/Limestone	1030
		Lamotte		Sandstone & Conglomerate	720
Precambrian Rocks			Basement Confining Unit	Granitic,Basic and Felsitic	>720

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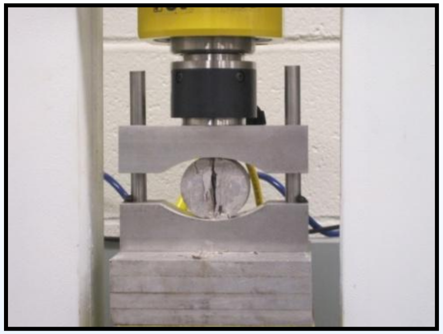
Rock strength properties

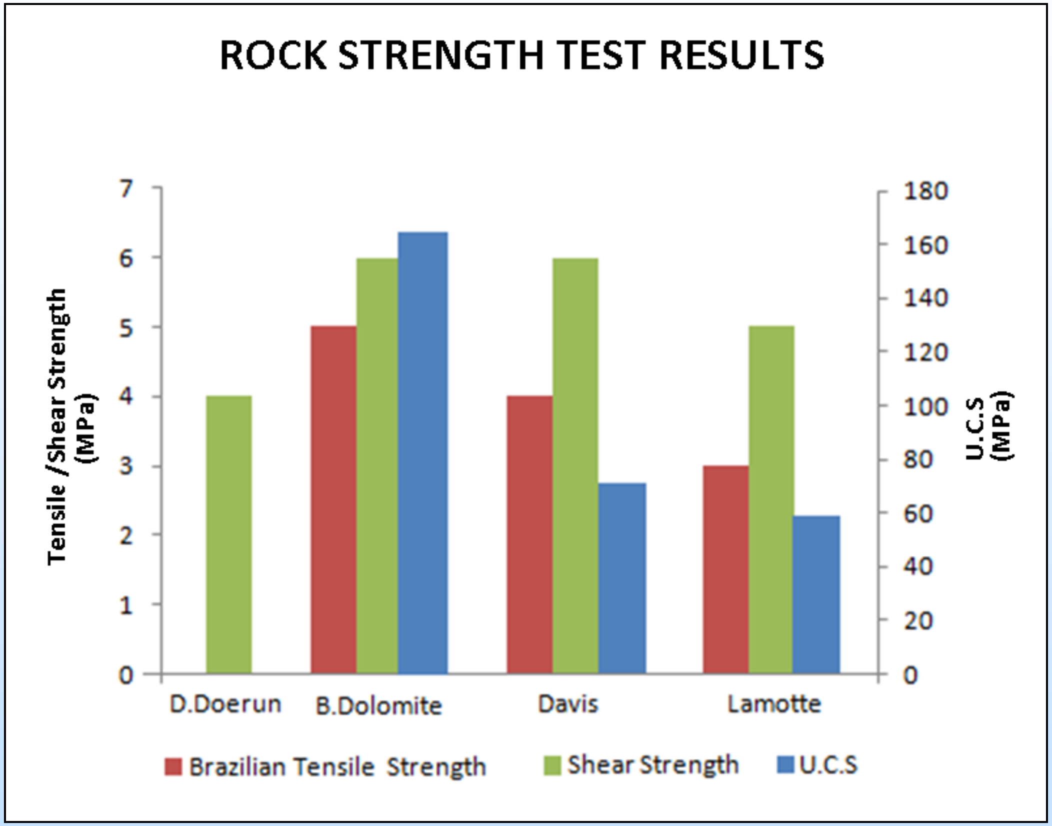


Brazilian Tensile Test

Triaxial Test

Shear Strength Test

U.C.S Test



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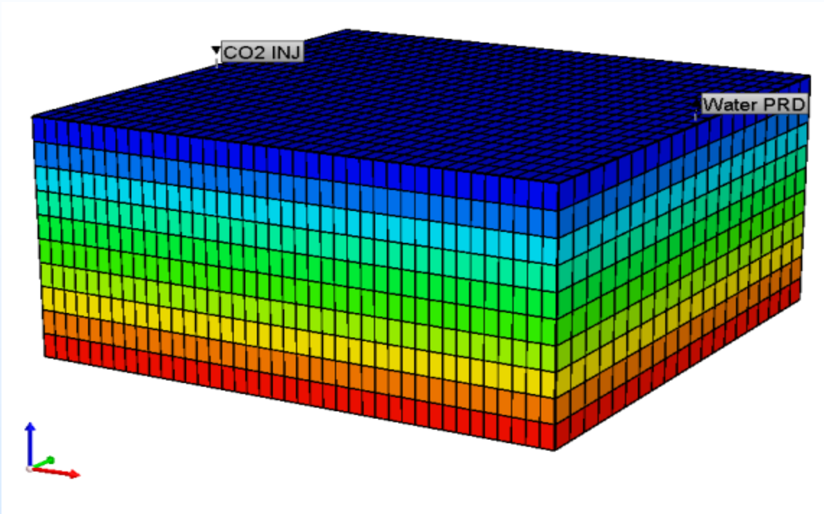
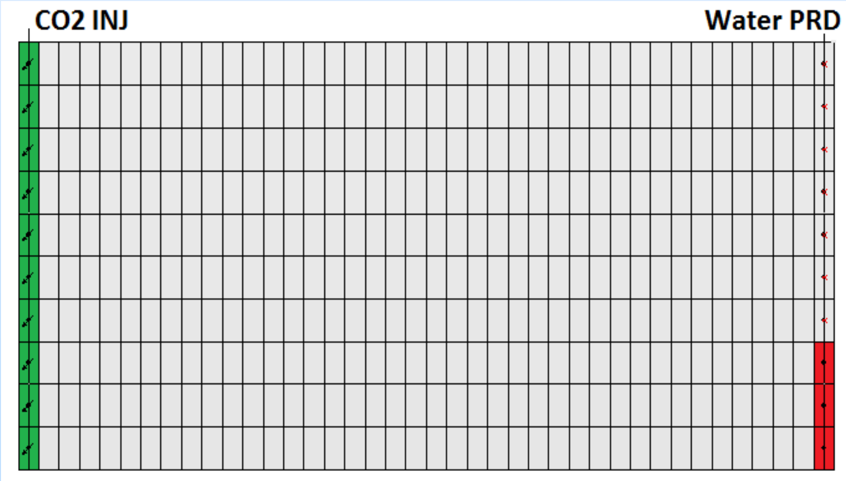
Base Model Description

Reservoir property	SI unit	Field unit
Formation Top	595 m	1952 ft
Thickness	57 m	187 ft
Porosity	10 %	
Permeability	20 md	
Rock compressibility	1E-9 1/kPa	
Reference pressure	4998 kPa	725 psi
Reference temperature	21.85 °C	595m-21.85; 652m-22.39
Bottom hole pressure	8238 kPa	
BHP Gradient	12.85-14.84 kPa/m	0.568-0.656 psi/ft
CO_2 injection rate	19740 m3/day	40 tons/d





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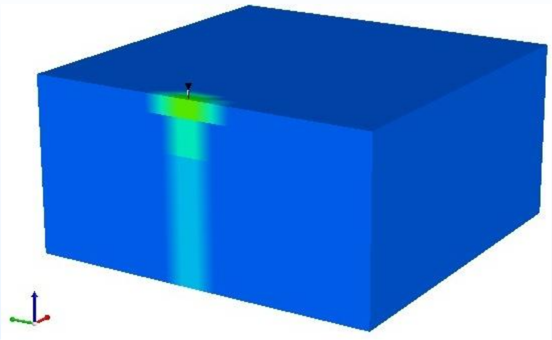
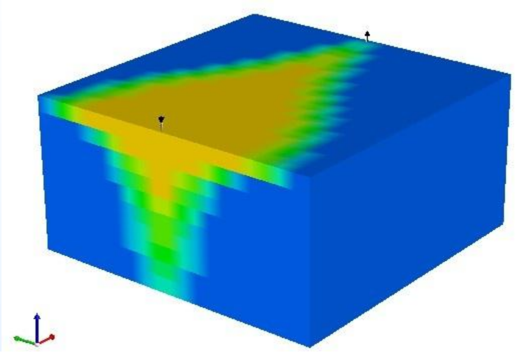
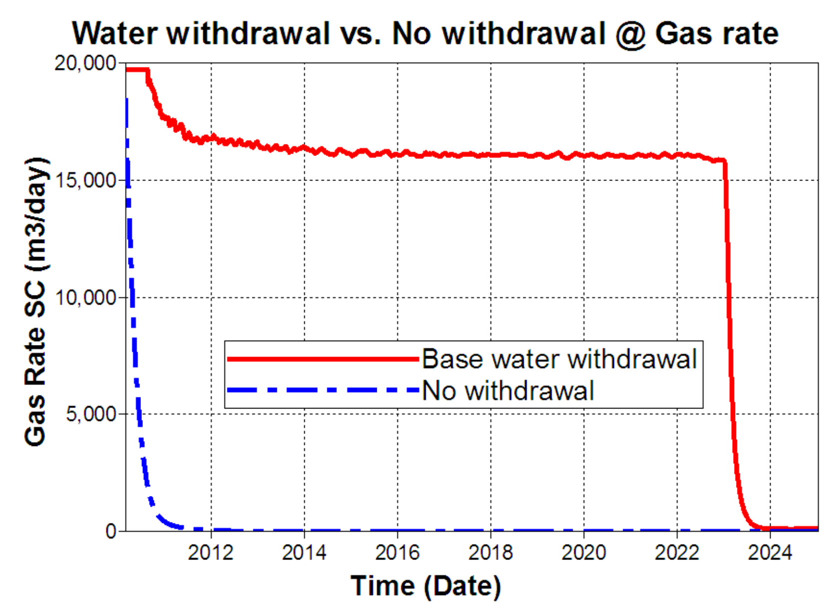
Water withdrawal in closed systems

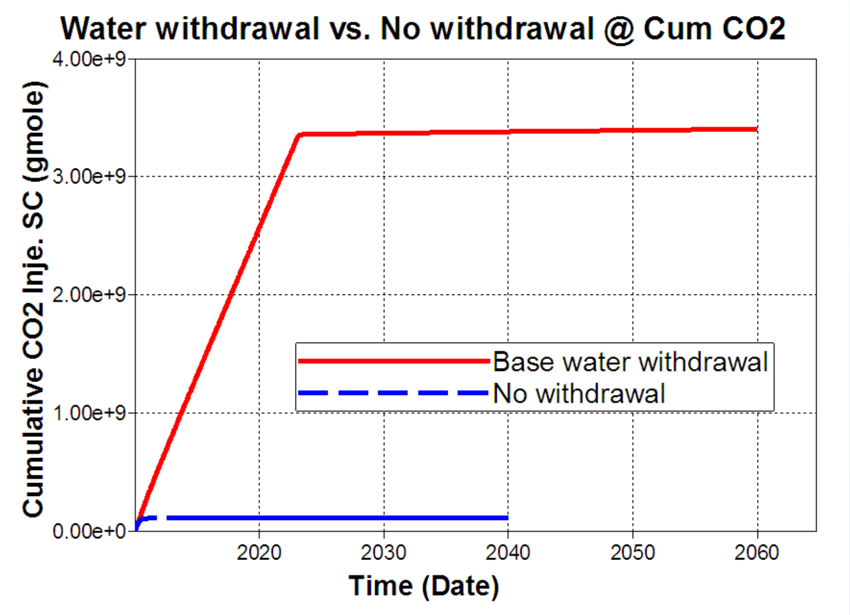
No withdrawal (Gas saturation)



Base case withdrawal (Gas saturation)







Case	CumINJ, % PV	InjRate at 10th year, m^3/day	Ave. Pressure at 10th year, kPa	Feasible injection time, year
Base withdrawal	5.32	16049.6	8087	13
No withdrawal	0.18	2.04	8413	1

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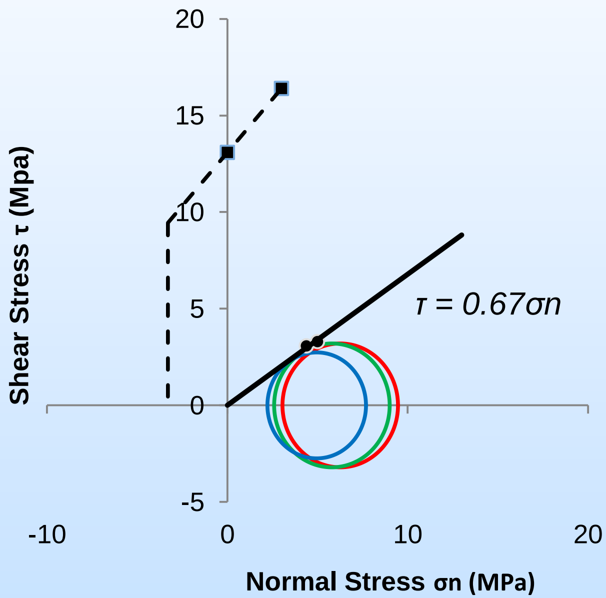
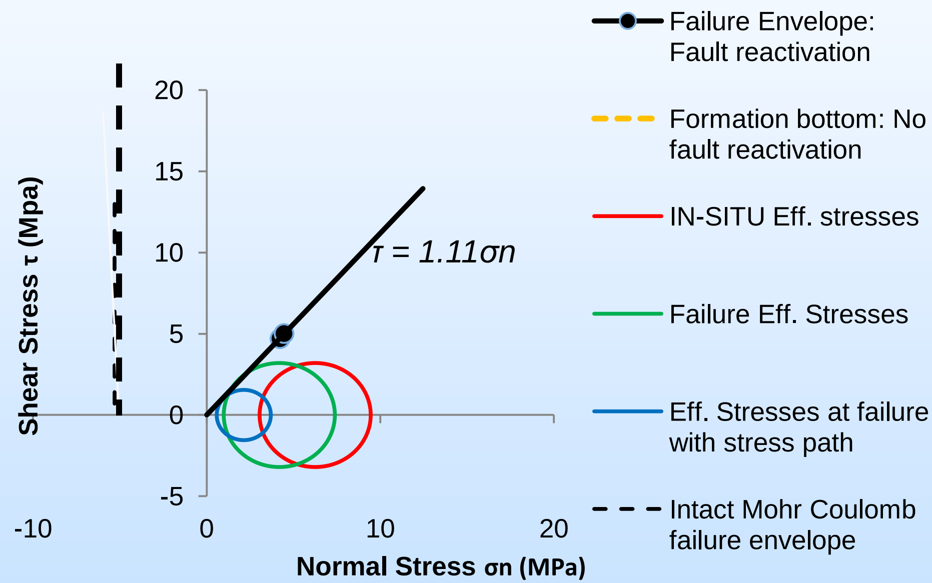
Fault reactivation and failure

Reservoir

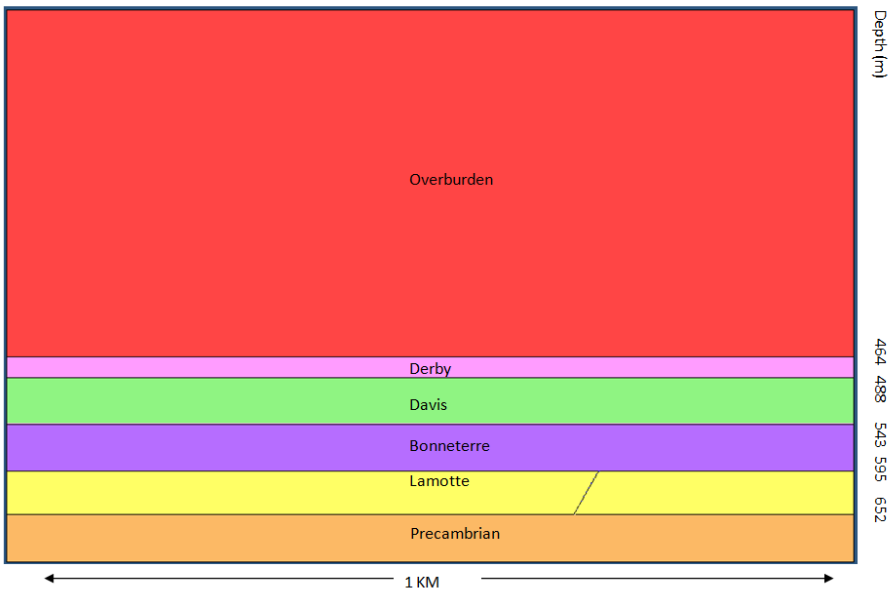


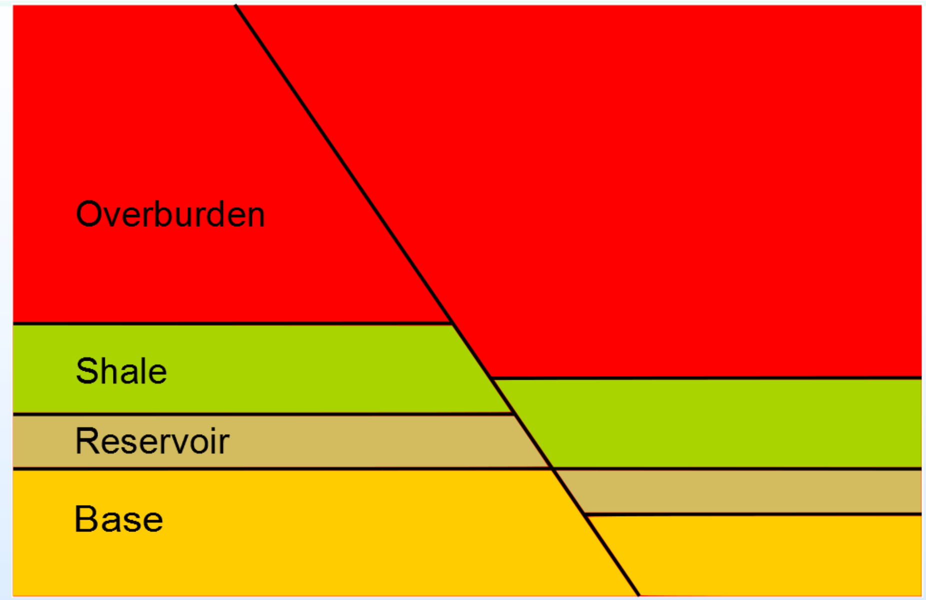
Cap rock



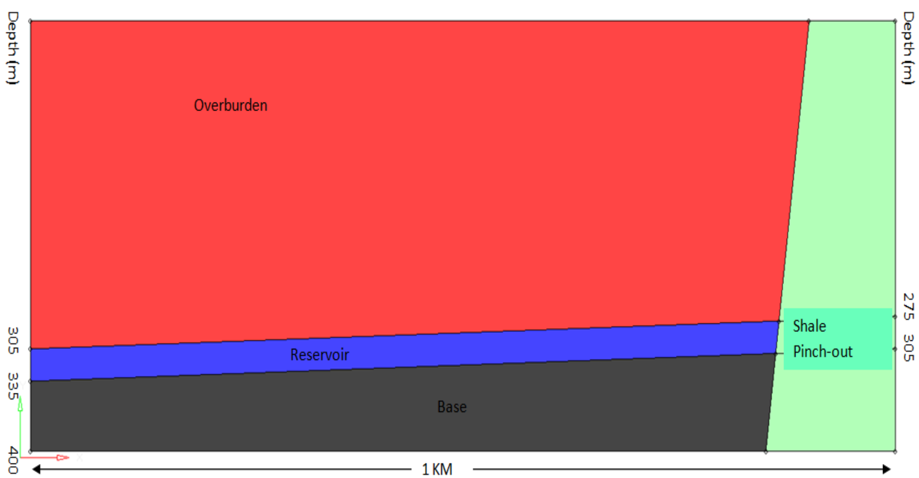
Potential injection trap system

Base Model with Fault

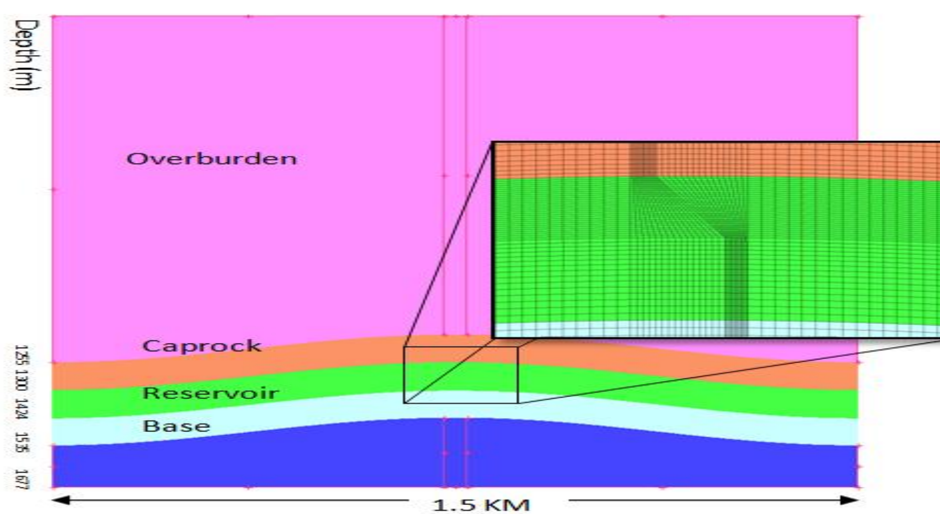




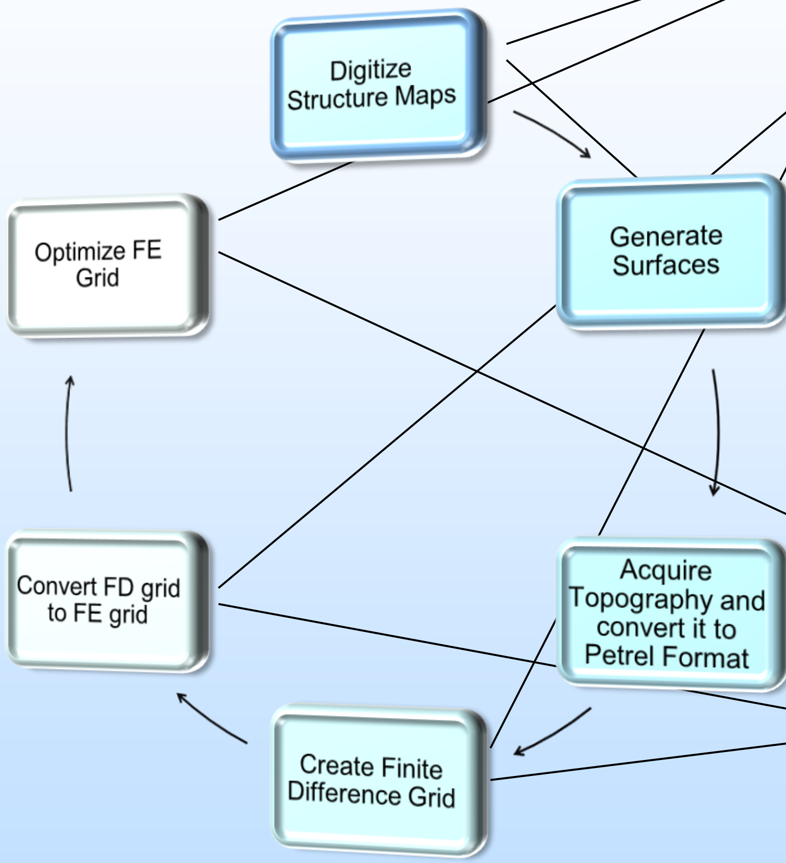
Pinch-Out Model

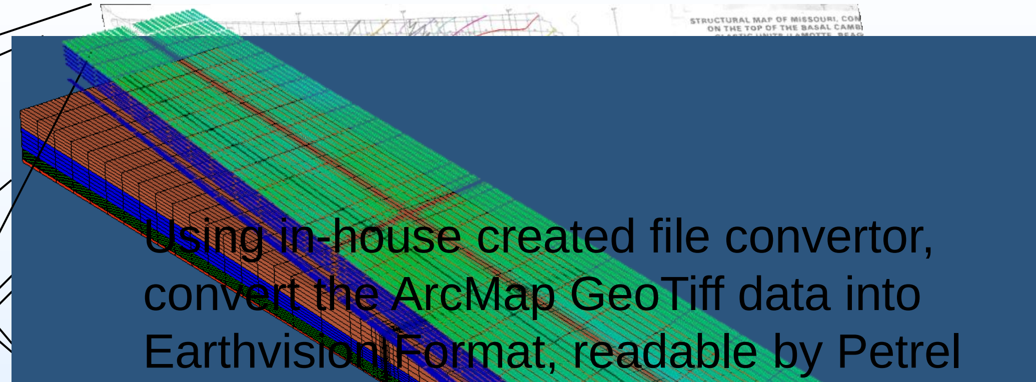


Anticline with Normal Fault Model

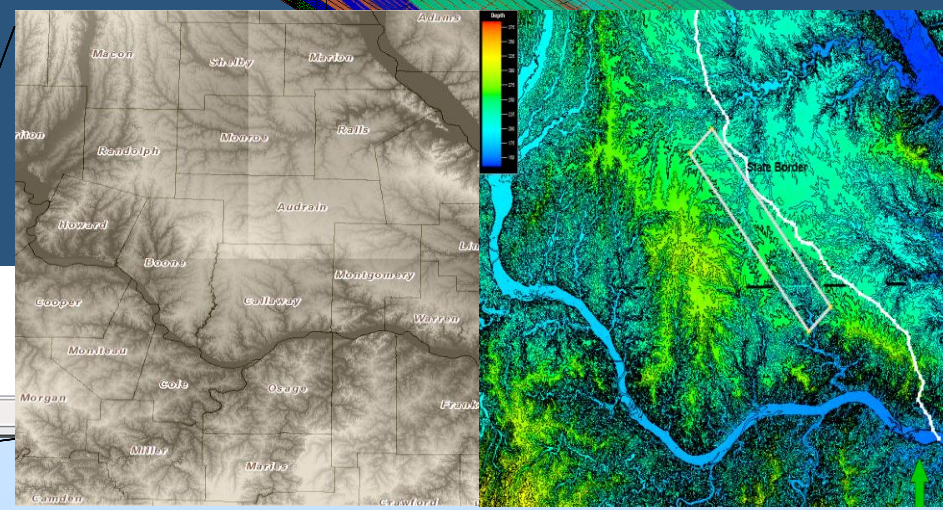


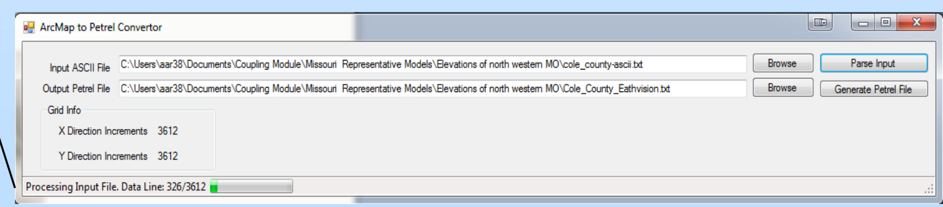
Shared Earth Model Work Flow





Using in-house created file convertor, convert the ArcMap GeoTiff data into Earthvision Format, readable by Petrel





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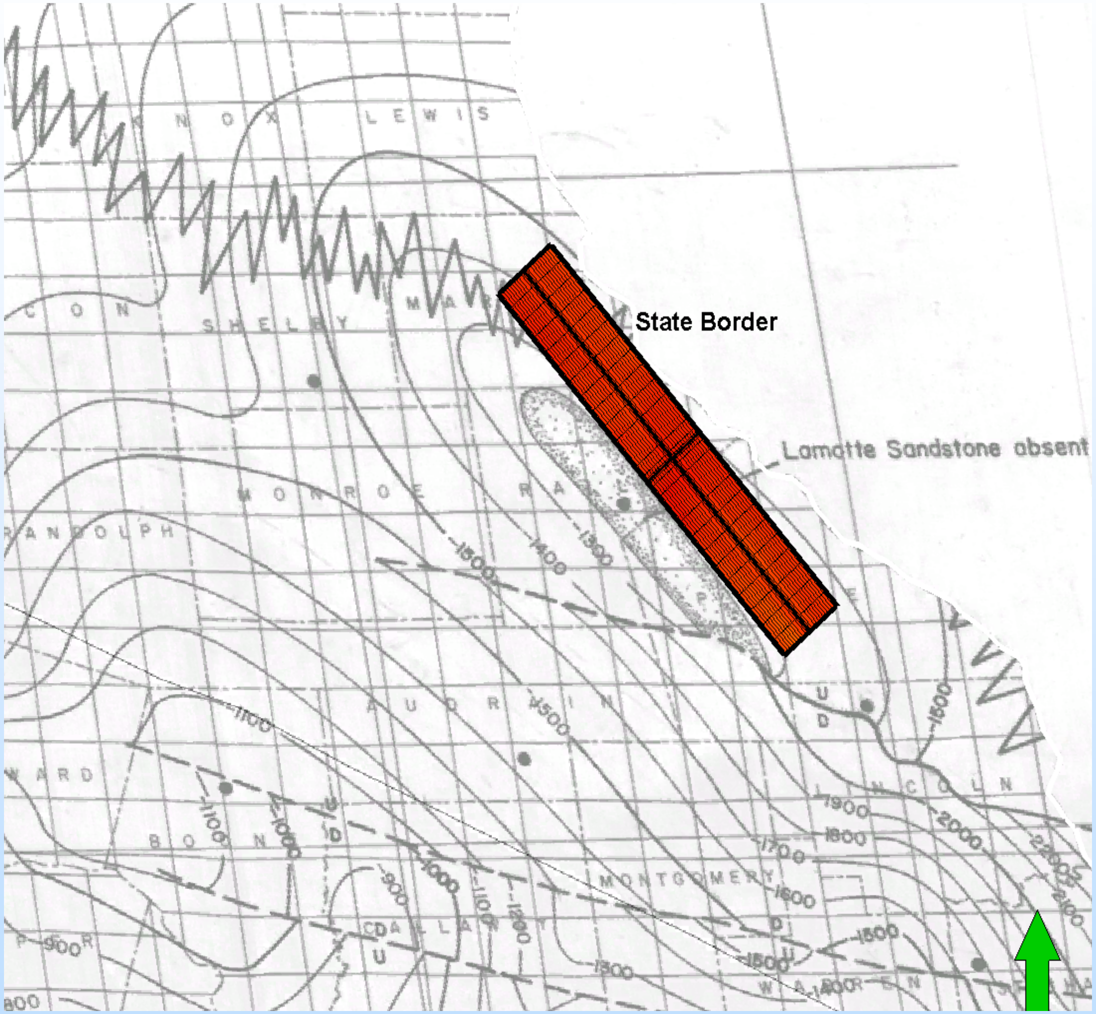
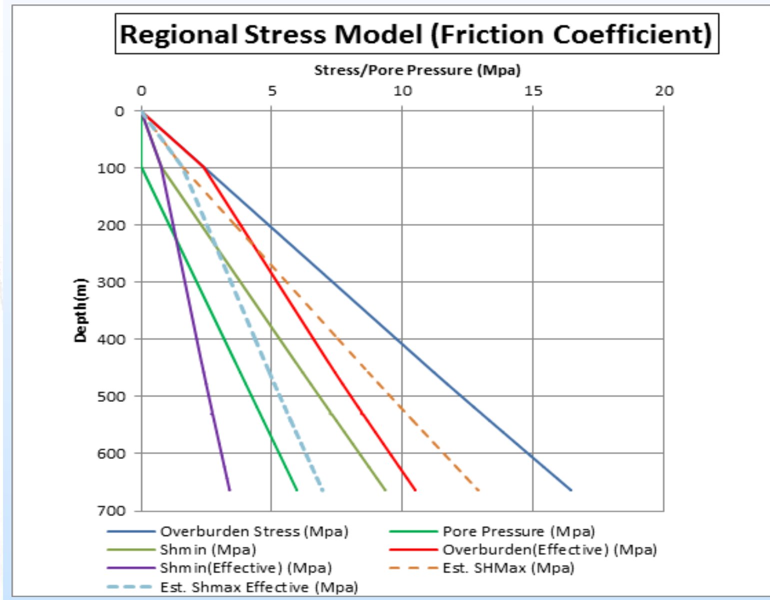
Missouri Pinch out Model





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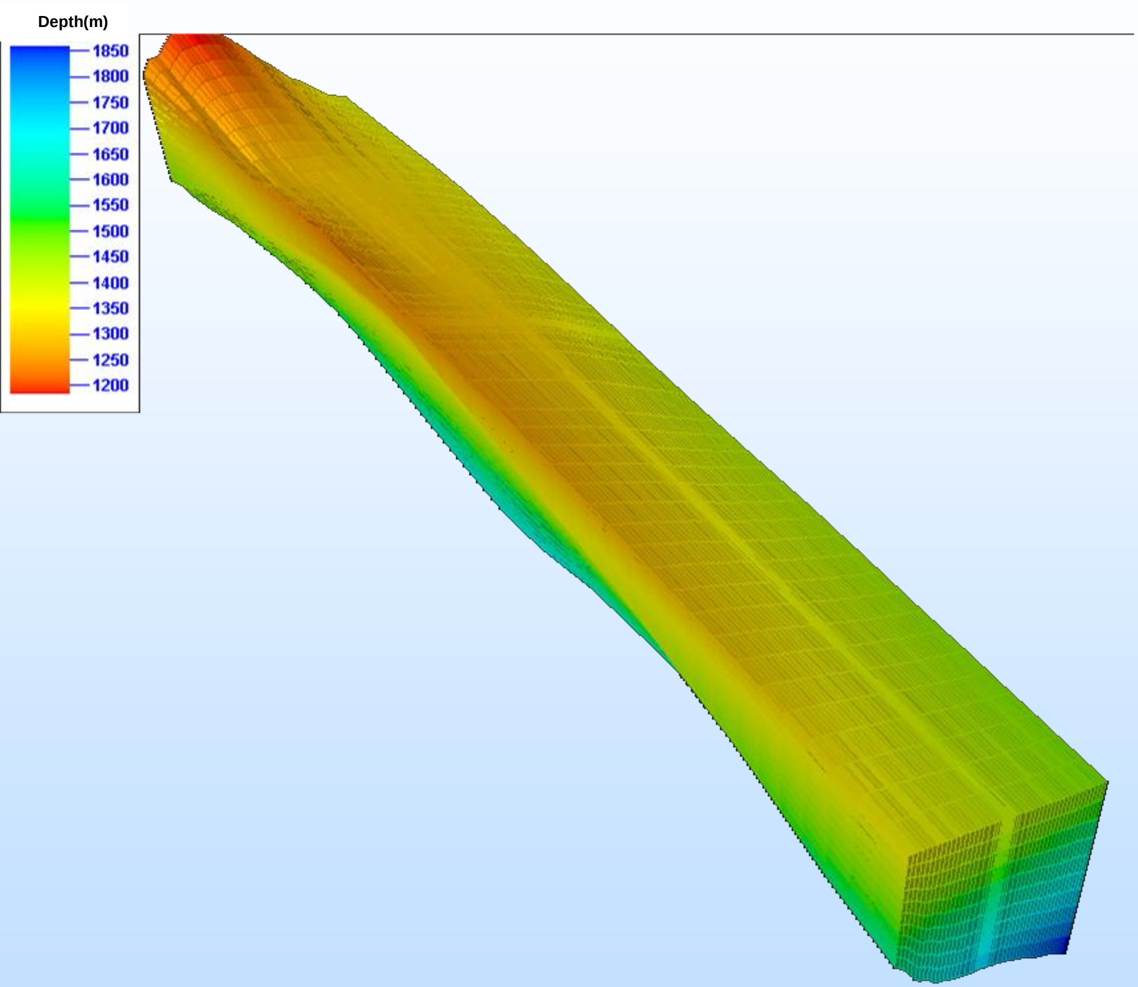
Pinch out shared earth model



The Final earth model:

- measures 70km X 16 km
- Has 74727 grid blocks
- Thickest Sandstone Part: 428 m
- Deepest Sandstone Depth: 1832 m
- Injection Rate: 200 kTons CO_2/year
- Injection Period: 85 years

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Outline Technical Status

- Leakage risk from CO_2 sequestration sites
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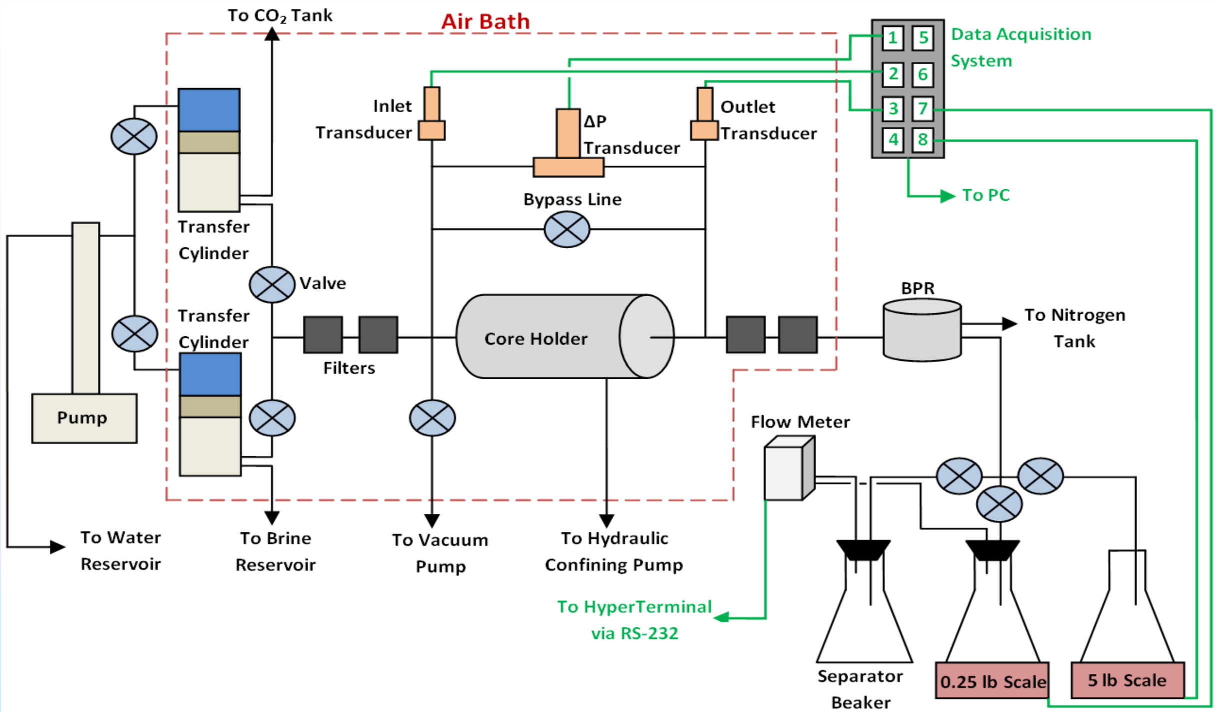
Evaluation of sealing materials to answer the following two questions

- How effective are the sealants plugging different fractures?
- Is the sealant long-term thermo-stabile in a CO_2 environment?

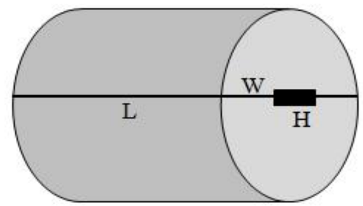
HPHT Core flooding Apparatus for Plugging Efficiency Evaluation



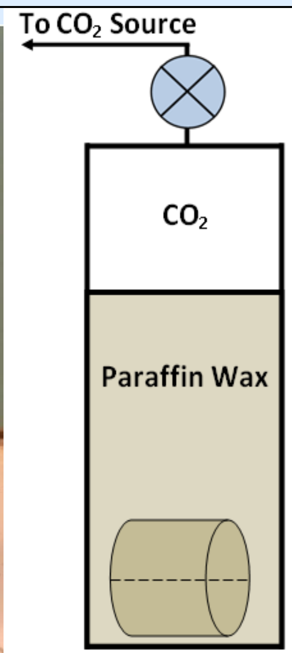
- CO_2/Brine Relative Permeability
- Evaluate the transportation of chemicals through porous media
- Evaluate the plugging efficiency of different plugging materials

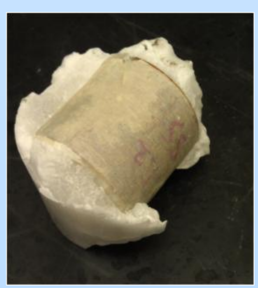
Evaluation of Sealing Materials

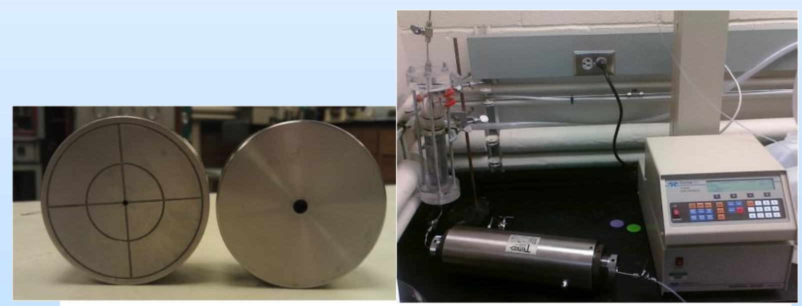
- Sealing Materials:
  - Marcit Gel: HPAM/Chrome Acetate
  - Silicate Gel
  - Paraffin Wax
  - Micro Cement
- Fracture Models

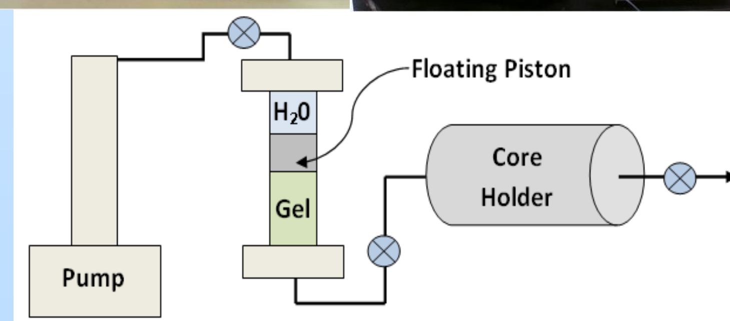


- Fracture Width = 0.5 mm
- Fracture Height = 9.5 mm
- Fracture Length = Full length of core

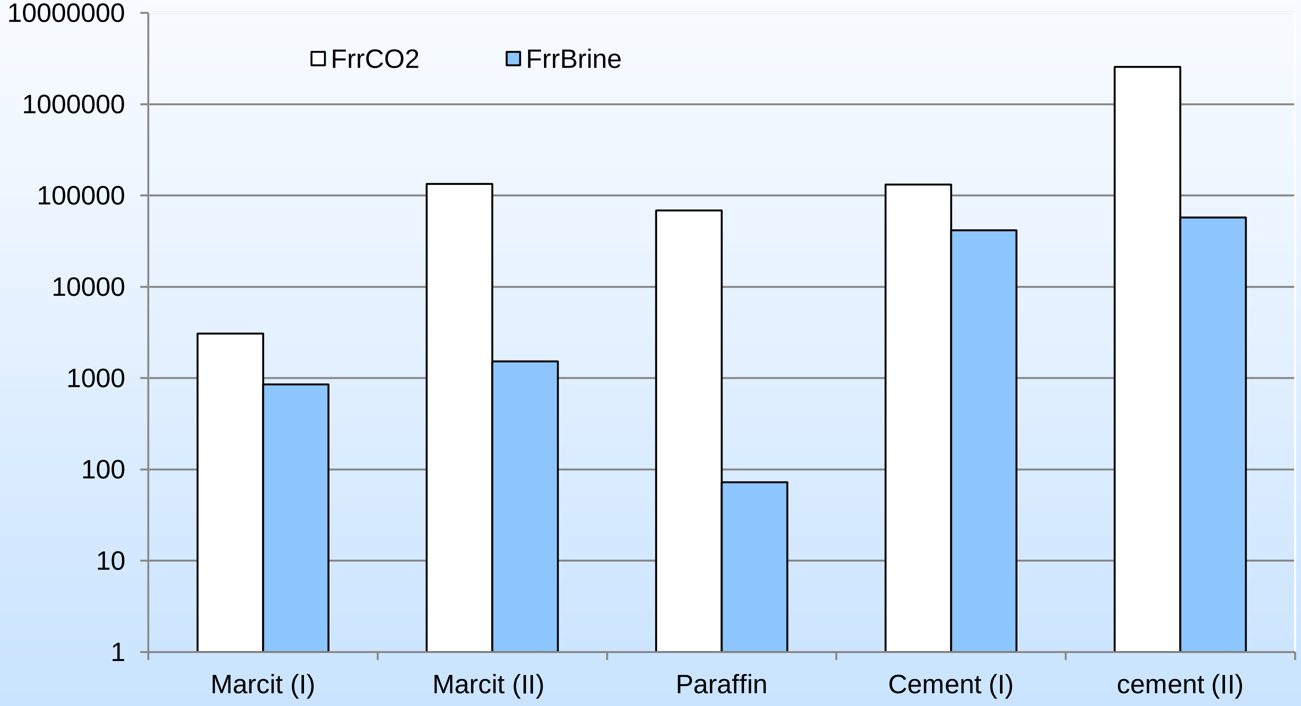








Sealing Results of Different Plugging Agents



Fracture width: 0.5 mm

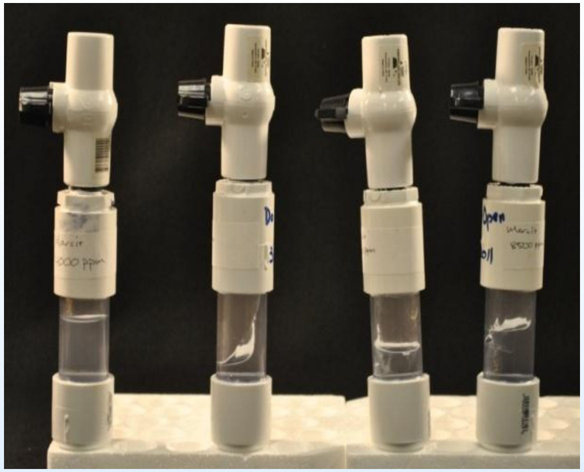
Marcit (I): SS (K=1.82 md); Marcit (II): BT (K=0.002 md)

Paraffin: SS (K=0.55 md);

Cement (I): Davis (K=0.0004 md) Cement (II): DPR (K=0.00004 md)

Thermal Stability of Plugging Agent in CO_2 Environment

Long term stability test tubes

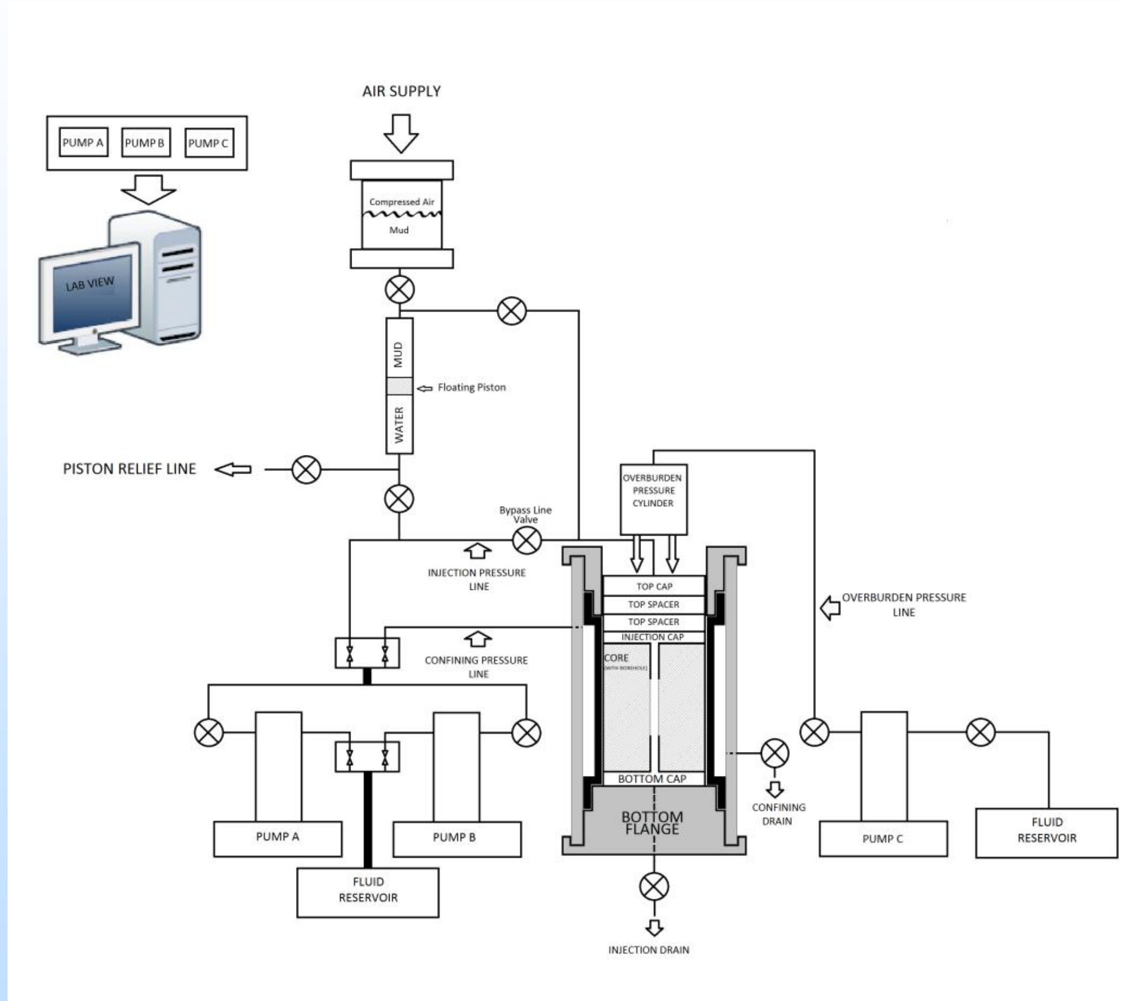


Evaluation results gel at room temperature

The gel is very stable in CO_2 Environment at shallow sequestration temperature

Time, (months)	Sample type Gel strength code			
	4000 ppm	5500 ppm	7000 ppm	8500 ppm
1	C	D	F	G
2	C	D	F	G
3	C	D	F	G
4	C	D	F	G
5	C	D	F	G
6	C	D	F	G
7	C	D	F	G

Apparatus to evaluate sealing effect under down hole conditions



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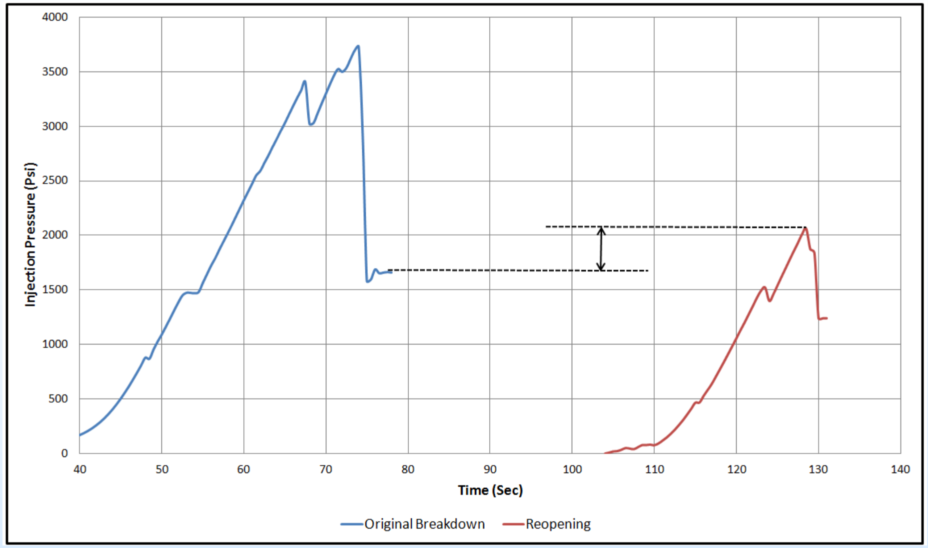
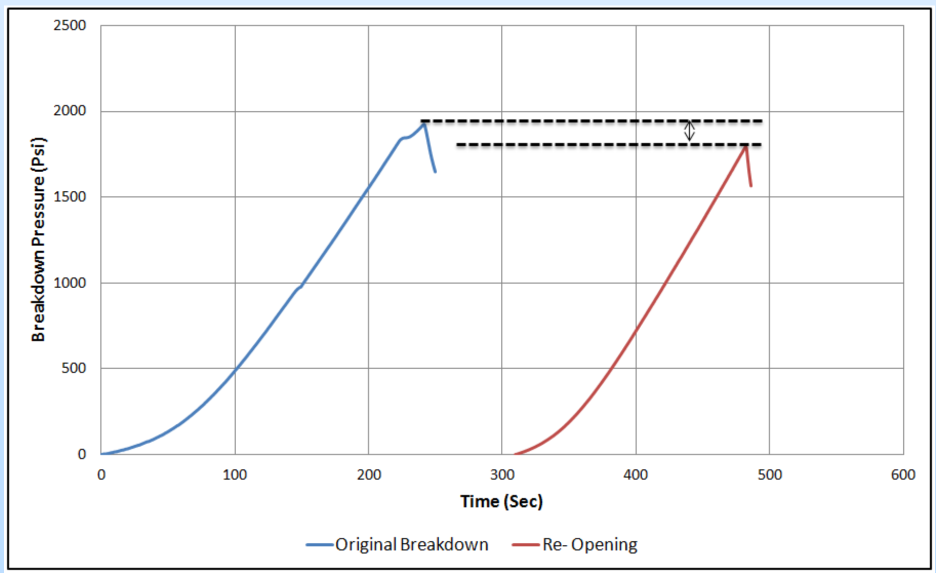
Fracture re-opens at higher pressure with temporary sealant





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Outline Technical Status

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Need for Coupled Reservoir Simulation

- Fluid flow simulators do not model geomechanics
- Geomechanical analysis packages can not handle multi-phase, multi-fluid systems
- There are mature simulators that can model each phenomenon precisely, but these packages do not talk to each other
- 8 Intel Xeon X5330 2.67GHz Processors, 72GB of RAM
- Part of Numerically Intensive Computing cluster 168 Nodes with Total 464GB of memory

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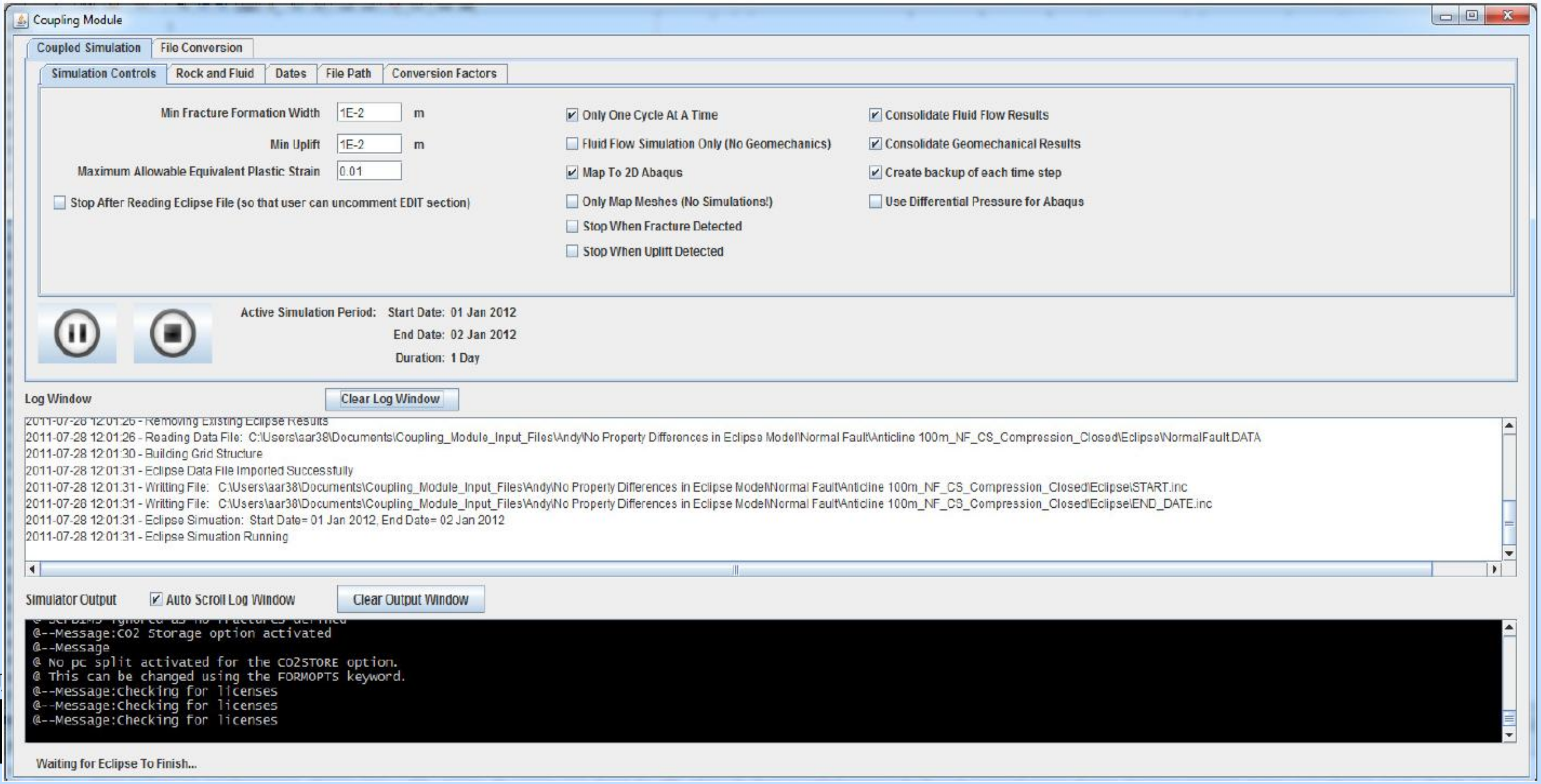
Feature requirements

- Executing simulations in Finite Difference Fluid Flow Simulator and Finite Element Geomechanical Analysis Package
- Reading Inputs/Outputs of the two simulators
- Interpreting the simulation results
- Correlating (mapping) the geometries in either simulator
- Updating input files based on the simulation

Coupled Geomechanical Reservoir Simulator

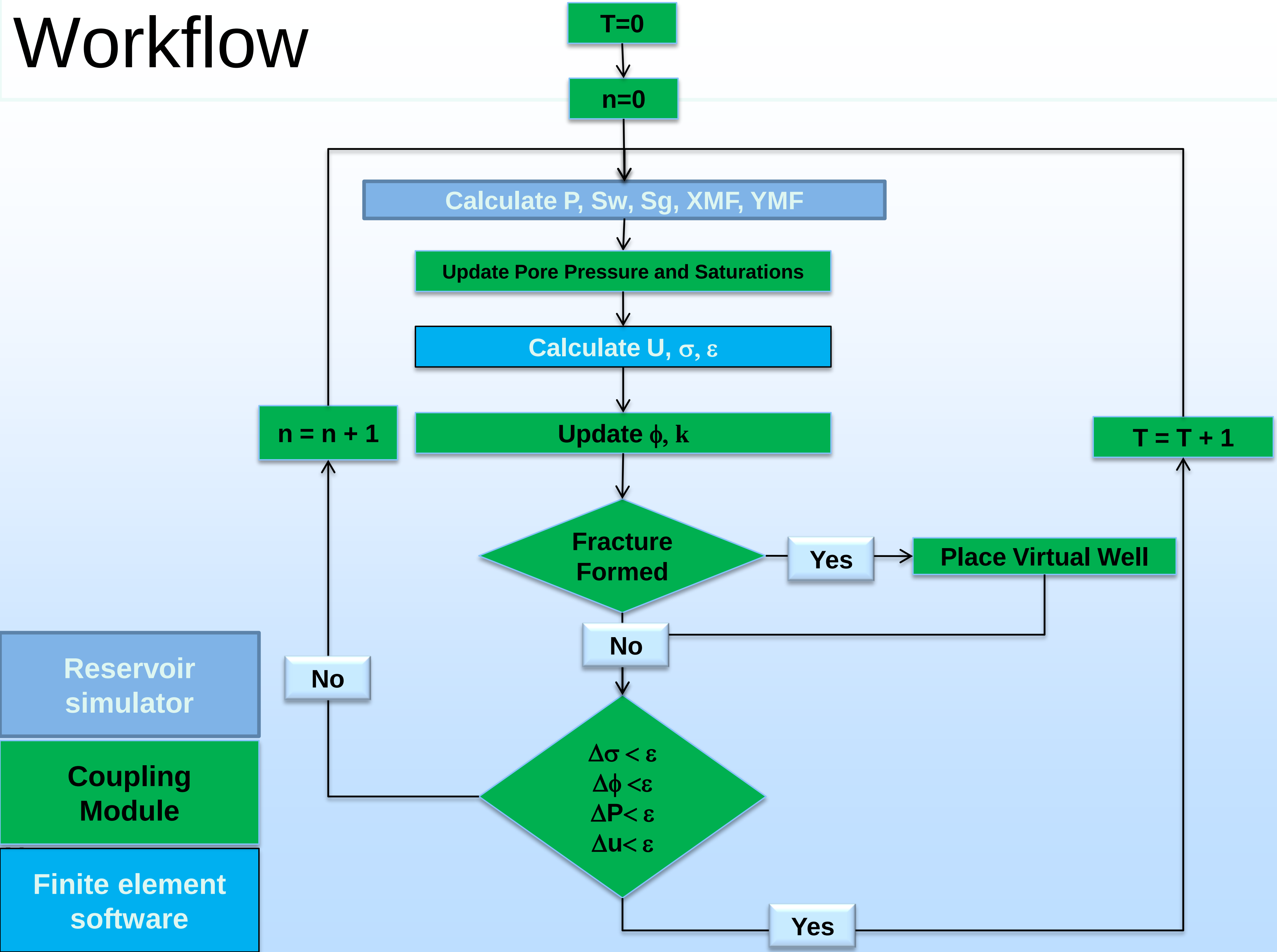
- Conversion of Petrel Surfaces to FE meshes
- Mapping different grid geometries for FE and FD
- Independent of FE Mesh Configuration (Tetras or Hexas)
- Capable of handling very complex geometries
- Automatic detection of fracture formation (Plastic Strain)



Coupled Geomechanical Reservoir Simulator

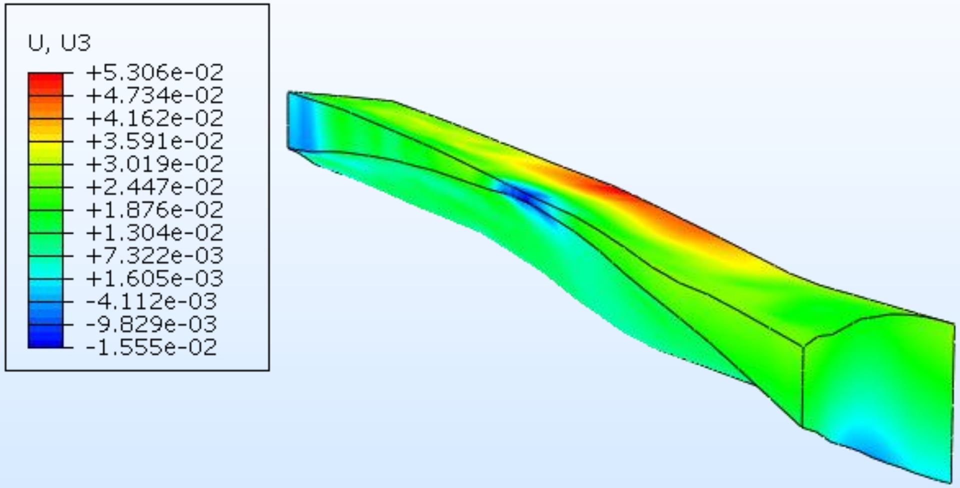
- Placement of Equivalent Virtual Wells in the Caprock upon detection of through going fracture formation/reactivation
- Periodic updating of FE Mesh and FD Parameters by mapping of the two meshes
- High Level OOP resulting in highly efficient memory management and feature flexibility
- The coupling module doesn’t include full pore elastic analysis for multiple fluid phases

Workflow

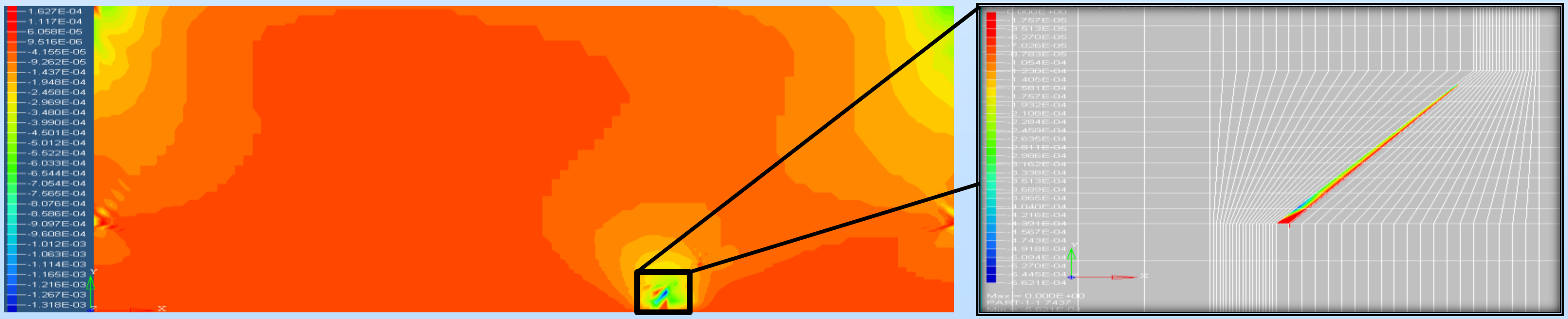

T=0
n=0
Calculate P, Sw, Sg, XMF, YMF
Update Pore Pressure and Saturations
Calculate U, σ, ε
n = n + 1
Update ϕ, k
T = T + 1
Fracture Formed
Yes
Place Virtual Well
No
No
Δσ < ε
Δϕ <ε
ΔP< ε
Δu< ε
Yes
Reservoir simulator
Coupling Module
Finite element software

Coupled Geomechanical Reservoir Simulator Capabilities

- Determination of fracture formation and placement of virtual wells
- Determination of uplift



- Determination of Seismicity



Vertical Displacement around faulted region = 1.42 mm

Fault Slip = 0.56 mm
Resulting Seismicity = 0.23 on Richter's Scale

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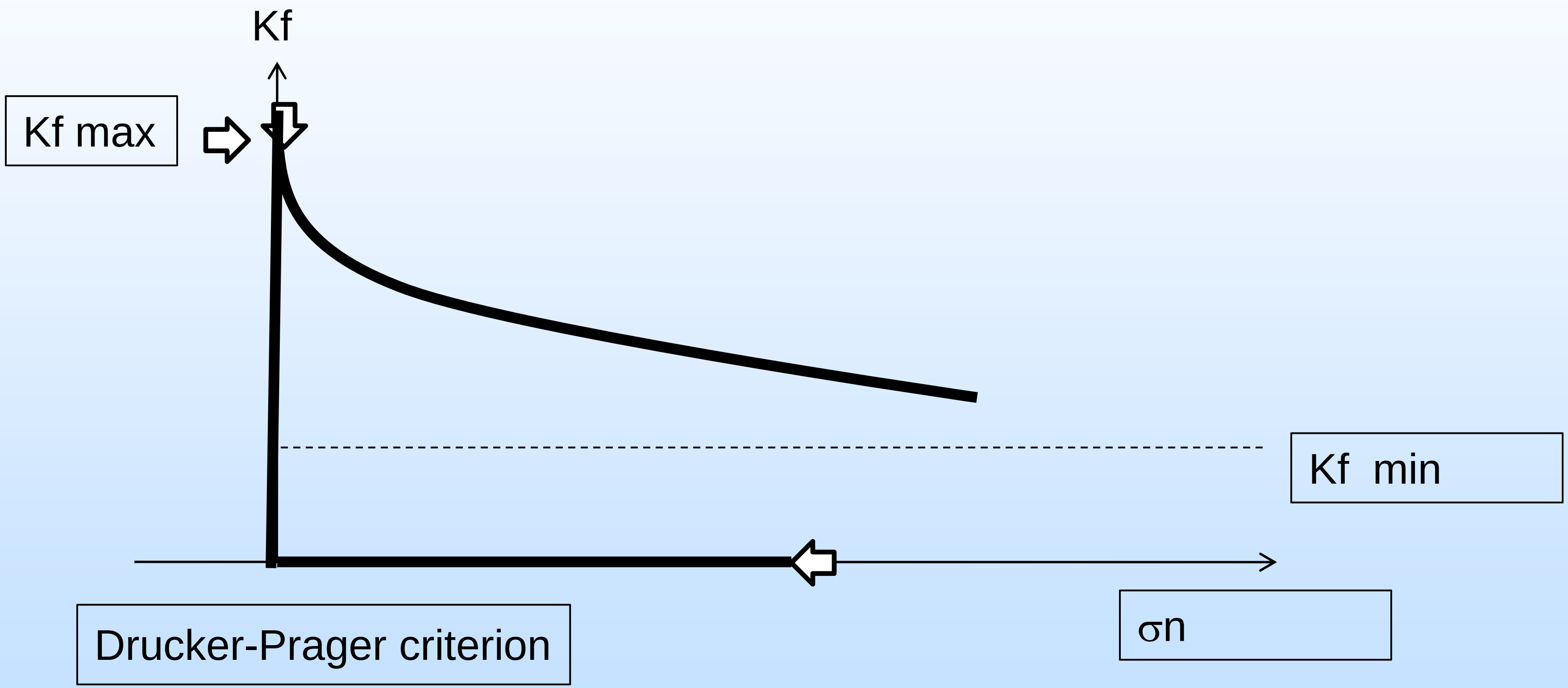
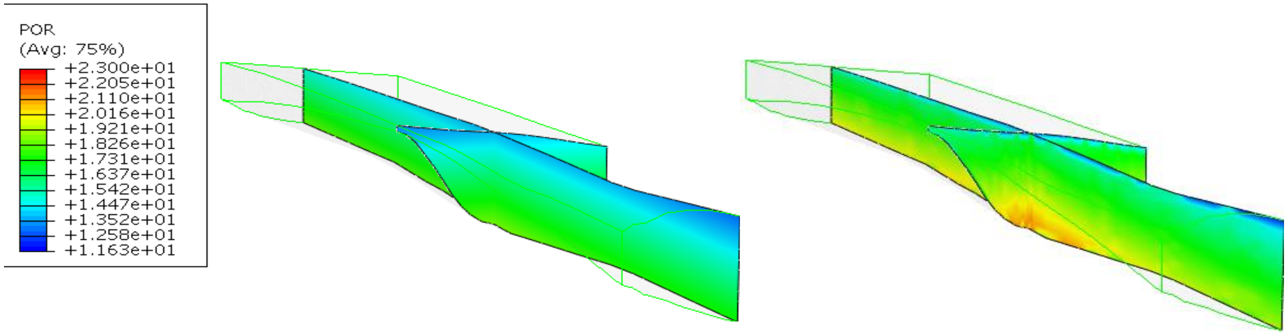
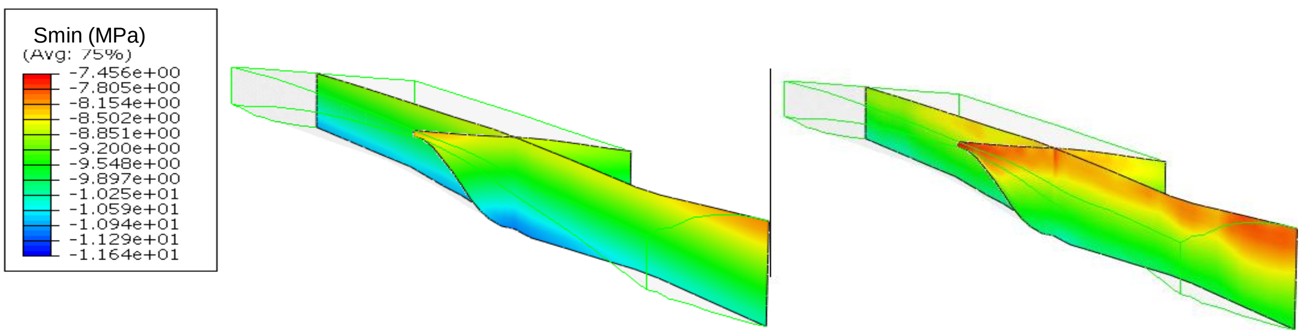
Fracture modeling, fracture permeability and seismicity prediction



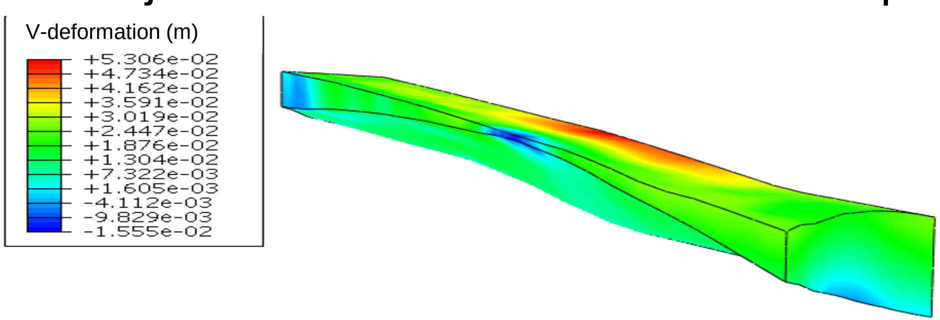
Pinch out structure simulation results



CO2 Injection increases the pore pressure in the Lamotte sandstone by 5MPa



CO2 Injection reduces effective minimum principal stress



Minor uplift without any seismic risk observed in the Lamotte formation after 85 years of CO_2 injection

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Accomplishments to date

- Capabilities have been developed to evaluate seal leakage, but not been applied to an actual injection site
- A detailed approach in how to create a realistic shared earth model from multiple sources when seismic data is not present
- Developed new laboratory equipments to evaluate sealant behavior in:
  - Fractures under reservoir pressure and temperatures
  - Shear fractures
  - Tensile fractures (hydro-fracturing) and in a near wellbore region
  - Long term stability of sealant when exposed to CO_2
- A coupled geomechanical reservoir simulator which is capable of:
  - Conversion of different grid geometries between Reservoir and FE mesh format
  - Mapping different grid geometries
  - Populating FD and FE models with corresponding data
  - Detecting plastic deformations and uplift
  - Modeling formed/reactivated fracture permeability
  - Determining CO_2 outflow to overburden
  - Determining fault slip tendency, slip magnitude and the resulting seismicity

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Summary

- In a shallow sequestration closed system only a few percent of the total volume can be injected with CO_2 for the shallow case

- CO_2 injectivity increases with increasing permeability variation, and increasing formation thickness or decreasing the vertical-to-horizontal permeability ratio

- CO_2 storage capacity depended heavily on formation heterogeneity and anisotropy

- Water withdrawal slows pressure build-up, allow CO_2 injection at a higher rate, thus greatly improve CO_2 storage capacity and CO_2 injectivity

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Summary cont…..

- Cement is the most effective fracture sealant material, however Portland based cements not expected to be stable when exposed to CO_2
- Polymers seals effectively and are stable when exposed to CO_2
- Coupled simulations shows that CO_2 plume can be different compared to reservoir simulations and leak into the cap rock
- Surface deformations is seen in the simulations (at levels which can be detected by satellites and be used as a monitoring techniques)

Appendix

Organization Chart

Sponsor
DOE

Project manager
Dr. Nygaard
Task 1

Shared earth model Dr. Nygaard Project lead	**Modeling** Dr. Eckert Project lead	**Laboratory experiments** Dr. Bai Project lead	**Functional expertise**
Task 2 (Imowo Akpan)			City Utilities of Springfield
	Task 3 (Fang Yang) Task 4 (Fang Yang) Task 6 (Paul Tongwa)	Task 5 (Aaron Blue, Paul Tongwa)	Dr. Bai
	Task 3 (Amin Amirlatifi) Task 4(Amin Amirlatifi) Task 6 (Amin Amirlatifi)		Dr. Eckert
Task 2 (Sudarshan Govandarijan)	Task 6 (AminAmirlatifi)	Task 5 (Ishan Kumar, Robert Link)	Dr. Nygaard

Project members

PI

Dr. Runar Nygaard, Assistant Professor, Petroleum Engineering

Dr. Baojun Bai, Associate Professor, Petroleum Engineering

Dr. Andreas Eckert,, Assistant Professor, Petroleum Engineering

Graduate students

Imowo Akpan, MS (Shared earth model development)
Amin Amirlatifi, PhD (Coupled modeling)
Aaron Blue, MS (Fracture filling materials)
Sudarshan Govandarijan, MS (rock mechanical testing)
Ishan Kumar, MS (shear fracture testing)
Robert Link (shear fracture testing)
Paul Tongwa, PhD (Fracture filling materials)
Fang Yang, PhD (Reservoir simulation)

City Utilities of Springfield

Gary Pendergrass/David Fraley

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Gantt Chart

TECHNICAL TASKS	FY2010				FY2011				FY2012			
	12/31	03/31	06/31	09/31	12/31	03/31	06/31	09/31	12/31	03/31	06/31	09/30
1.0 Project Management, Planning, and Reporting	→	→	→	→	→	→	→	→	→	→	→	→
2.0 Development of a shared earth model	→	→	→	→								
2.1 Geological and petrophysical model	→	→	→	→								
2.2 Geomechanical characterization	→	→	→	→	→							
2.3 Rock mechanical testing	→	→	→	→	→	→	→					
3.0 Model development	→	→	→	→	→							
3.1 D Finite element (FE) model construction		→	→	→								
3.2 Calibration of the 3D FE model to the in situ state of stress			→	→	→							
3.3 Static reservoir modeling	→	→	→	→	→							
Task 4.0 Coupled modeling				→	→	→	→	→				
4.1 Coupling of res. and geomech. model				→	→	→						
4.2 Coupled modeling reservoir model						→	→	→				
4.3 Coupled modeling – geomech. model							→	→				
4.4 Res. and geomech. results analysis								→				
5.0 Experiments of fracture remediation	→	→	→	→	→	→	→	→				
5.1 Design of fracture filling materials	→	→	→	→	→	→	→	→				
5.2 Fracture filling shear apparatus test						→	→	→	→	→		
5.3 –Fracture filling triaxial test					→	→	→	→	→	→		
6.0 Numerical verification of fracture remediation									→	→	→	→
6.1 –Sealant fracture permeability model									→	→		
6.2 Development of MEM structures									→	→	→	→
6.3 Coupled modeling of MEM structures									→	→	→	→

Bibliography

– Tongwa, P., Nygaard, R. and Bai, B., 2012, Evaluation of a Nanocomposite Hydrogel for Water Shut-off In Enhanced Oil Recovery Applications: Design, Synthesis and Characterization. Journal of Applied Polymer Science: APP-2011-11-4184, available at: http://onlinelibrary.wiley.com/doi/10.1002/app.38258/

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BACK UP SLIDES

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DOE Carbon Storage RD Project Review Meeting, August 21-23, 2012 , Pittsburgh, PA

Development of a Coupled Module for Evaluating Leakage Risk and Seismicity with CO_2 Injection

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Abstract

Geologic CO2 sequestration has been identified as a possibility to mitigate high emissions of CO2 into the atmosphere and the resulting greenhouse effects, provided that a thorough understanding of the storage site is acquired. In order to determine safe sequestration limits, i.e. the maximum sustainable pore pressure, coupling between the multiphase fluid flow and resulting rock deformations in the reservoir-caprock system is required. In order to study these effects, an iterative partial coupling module is developed in Java that uses the compositional fluid flow simulator Eclipse, for fluid flow simulations and the geomechanical analysis package ABAQUS/CAE, for stress analysis and determination of plastic failures. The coupling module uses a shared earth model that is correlated between the two simulators through determination of relative spatial position of points in the two meshes. Fluid flow properties determined by Eclipse such as saturations, pore pressures and temperatures are mapped and transferred into the finite element model and the resulting state of stress and deformations from ABAQUS are used to calculate the variations in porosity and permeability of Eclipse grid as the coupling parameters. In the advent of plastic deformation or fracture reactivation, extent, direction and aperture of the resulting fractures are calculated and a virtual well is placed in the corresponding grid block(s) in Eclipse mesh so that the fluid flow through the fracture can be determined. The presented coupling module is capable of determining uplift, fault reactivation and the resulting seismicity, in case the model is faulted.

Introduction

Iterative partial coupling is a two way coupling technique that uses a multiphase fluid flow simulator and a geomechanics simulator. The nonlinear iterations at each time step involve fluid flow and nodal displacement calculations that are carried out sequentially and the two simulators are coupled through pore volume calculations.

At each iteration, the fluid flow simulator determines the pore pressure, fluid saturation and temperature distribution throughout the model. Assuming an isothermal process is taking place, the temperature variation can be neglected and pore pressures and saturations are fed into the geomechanics simulator by rewriting the corresponding input data files of the simulator. Restarting from the previous state of stress and displacements, the geomechanics simulator calculates nodal displacements and the state of stress and strain under the new pore pressure distribution, along with the possibility of rock failure and the extent of such failures. The new state of stress is then used to update the permeability and porosity of reservoir and the corresponding input data files of the fluid flow simulator are updated accordingly. In the advent of rock failure or reactivation of existing fractures, the orientation and location of failure are checked to identify caprock penetrating fractures. A fracture is emulated by placement of a virtual well that yields the same fluid flow rate as the fracture.

Modeling Approach

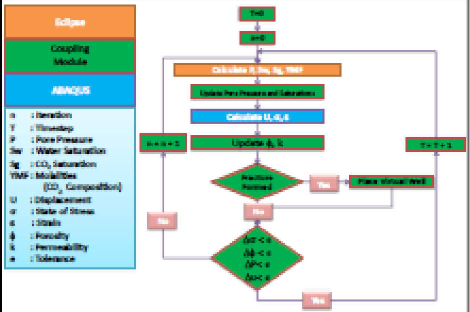

Figure 1 - Work flow of the coupled reservoir modeling

Modeling Approach(Cont'd)

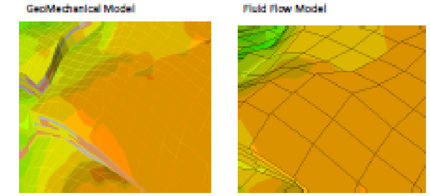

Figure 2 – Geomechanical mesh compared to finite difference grid

Assuming that the FD grid is the coarser of the two discretizations, Figure 2, one or more than one FE element will either lay exactly at the boundaries of the FD grid block or inside the boundaries of it, thus the coupling module needs to determine the grid block that surrounds each element from the finite element mesh. This process is referred to as the mapping of the two discretizations. Mapping is done through determination of the element centroid and calculating number of times that a ray drawn from the centroid to the origin cuts through the sides of each FD grid block. This technique enables us to overcome the limitations of current simulators in terms of discretization and precise handling of discontinuities.

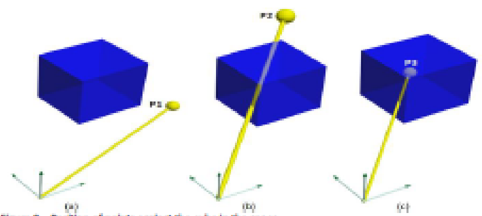

Figure 3 – Position of points against the cube in the space

A point in space, centroid in this case, is inside a cube if and only if the number of times a ray drawn from that point cuts through the sides of the cube are an odd number. For example, points P1 and P2 (Figure 3) are outside the cube because the rays drawn from P1 does not cut through the cube and the ray drawn from P2 cuts through two sides of the cube, an even number. On the other hand, point P3 is inside the cube, because the ray drawn from this point cuts through one side of the cube, an odd number, and this cube is assigned as the container of point P3.

After reconstructing the two meshes and determining spatial position of each point and correlating them, the coupling module assigns the updated simulation results to corresponding nodes and update the input data for the other simulator.

The new porosity value in the FD model is calculated using:

$$\phi^{n+1} = \phi^{n} + \alpha(\varepsilon_v^{n+1} - \varepsilon_v^{n}) + \frac{1}{Q}(P^{n+1} - P^{n})$$

Where ϕ^n is the existing porosity, at pore pressure P^n and volumetric strain ε_v^n and ϕ^{n+1} is the new porosity resulting from the new pore pressure, P^{n+1} and the new volumetric strain ε_v^{n+1} and Q is the Biot parameter.

Should an element undergo a plastic strain as determined by Mohr-Coulomb or Drucker-Prager criteria that results in fractures forming in it, the coupling module will increase the permeability of that element by the equivalent fracture permeability:

$$k_f = k_0 \exp(-C.\sigma_n')$$

Applications:

- Uplift detection
  Determination of the vertical displacement
- Fault reactivation and seismicity
  Determination of the seismic moment from slip distribution: $M_0 = G*A*D$
  Determination of the moment magnitude: $M_W = \frac{\log(M_0)}{1.5} - 10.73$

Simulation Results

In order to validate our approach, a coupled reservoir simulation model of a pinch out structure for CO_2 sequestration was developed that measures 70km X 16 km, has 74727 grid blocks and is subjected to 200 kTons of CO_2 injection per year for a period of 85 years.

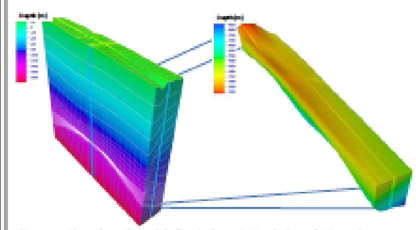

Figure 4 – Shared earth model of a pinch-out in North-East of Missouri

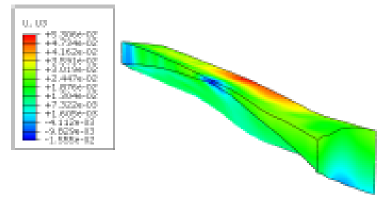

Figure 5 – Uplift observed in the Lamotte formation after 85 years of CO_2 injection

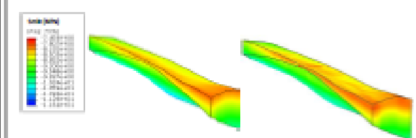

Figure 6 – CO2 injection reduces effective minimum principal stress

Conclusions

- Coupled fluid flow and geomechanical simulation is necessary for proper modeling of CO_2 sequestration projects, especially in shallow aquifers where high pressure gradients may result from injection of CO_2.

- Adequate meshing techniques that meet the requirements of fluid flow and geomechanics analysis simulators need to be employed so that realistic modeling of existing geologic features, e.g. faults or fractures, can be achieved.

- In an effort to model and mitigate the risk associated with injection of CO_2 in a shallow aquifer, a fully automated coupled geomechanical reservoir simulator is developed that is capable of mapping different grid geometries, populating finite difference and finite element models with corresponding data, detecting plastic deformations and modeling formed/reactivated fractures in caprock by placing equivalent virtual wells at the location of the fracture and thus measuring amount of CO_2 outflow to upper formations.

Acknowledgment

The authors gratefully acknowledge financial support from US Department of Energy's National Energy Technology Laboratory under grant # DE-FE0001132.

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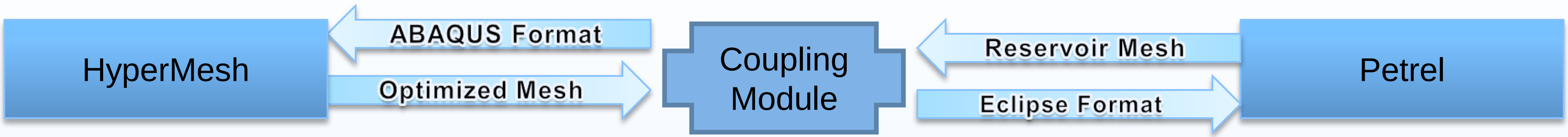
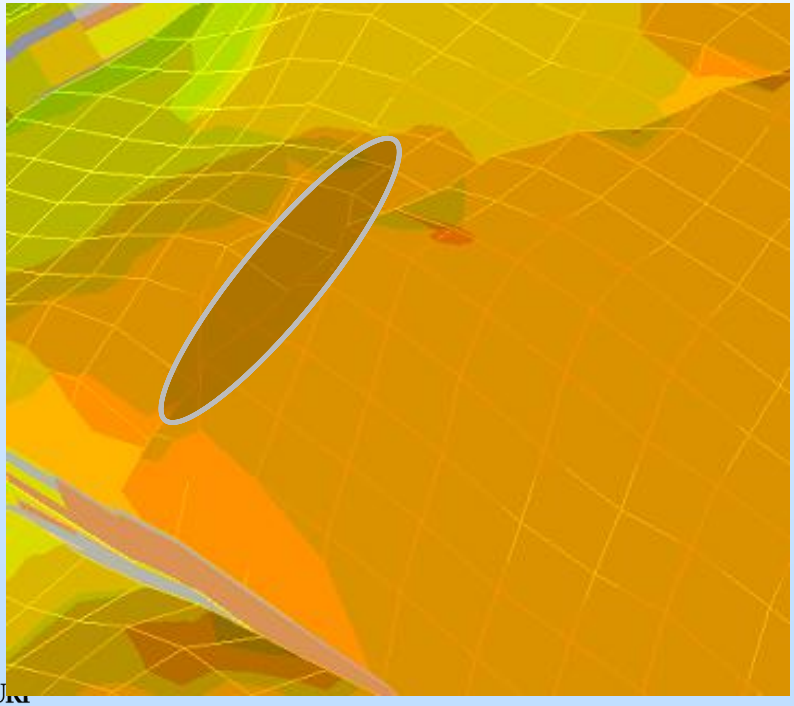
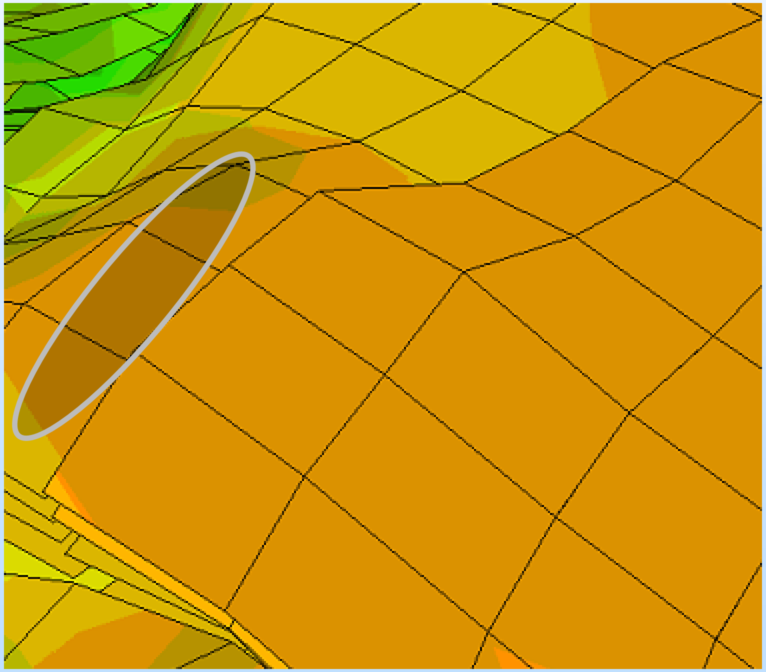
Precise Geometry Modeling



GeoMechanical Model

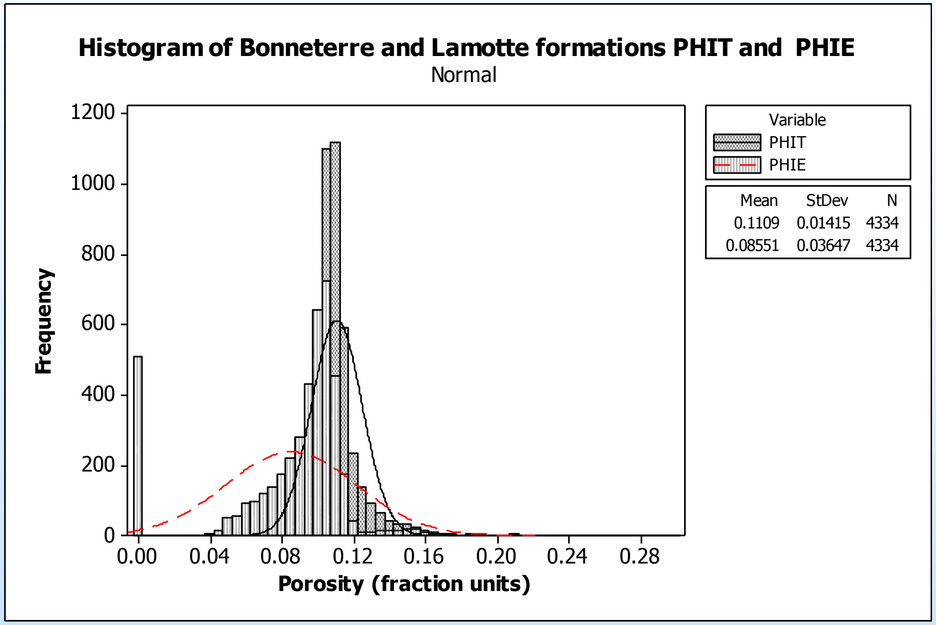


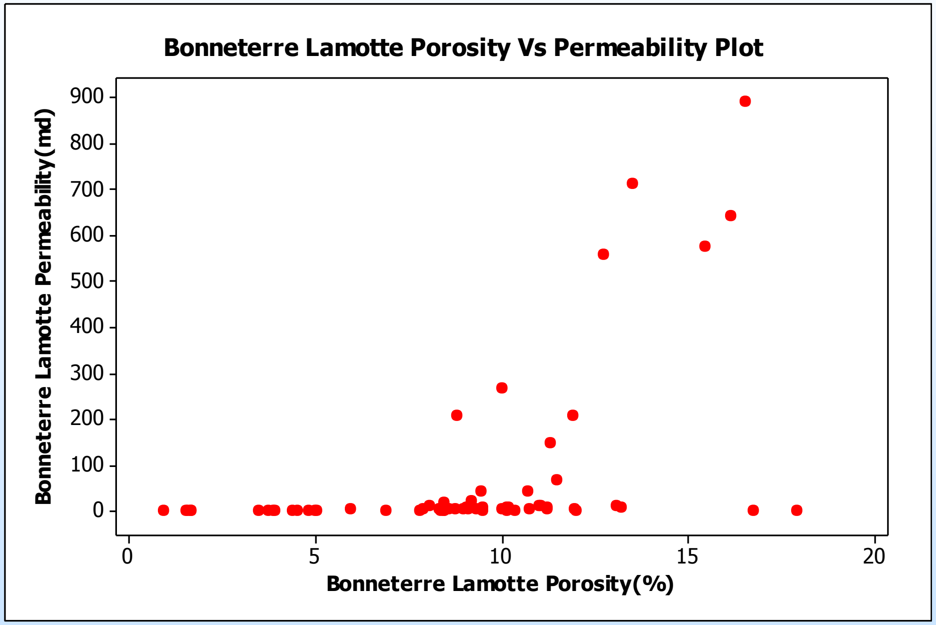
Fluid Flow Model



Loss of Precision!

Porosity and permeability





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Object Oriented Approach

Element

Child Nodes

- Node 1
- Node 2
- Node 3
- Node 4
- Node 5
- Node 6
- Node 7
- Node 8

Mapping

- Grid Block

Properties

- Centroid
- Stress
  Strain
  Displacement

Grid Block

Mapping

- Element 1
- Element 2
- Element 3
- Element 4

Properties

- Location
- K
  P
  Sw
  Sg
  ϕ
  XMF
  YMF

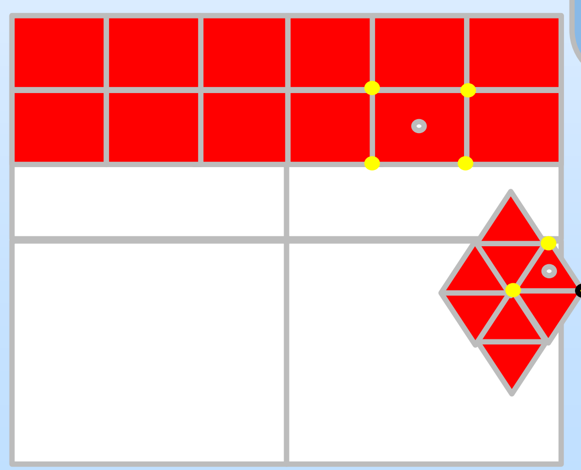
Node

Properties

- Location
- Stress
  Strain
  Displacement

Parents

- Element 1
- Element 2
- Element 3
- Element 4



Fracture permeabilty modeling

$$k_f = k_0 \exp(-C.\sigma_n')$$

k_0 is the initial permeability
C=0.27 from Lab results for shale

Virtual Well
r_{weq} = (K_f * ϕ * K_{aq} / h)
ϕ = Porosity of Aquifer
K_{aq} = Permeability of Aquifer
r_{weq} = Radius of Equivalent Virtual Well
h = Height of virtual well = 1 m

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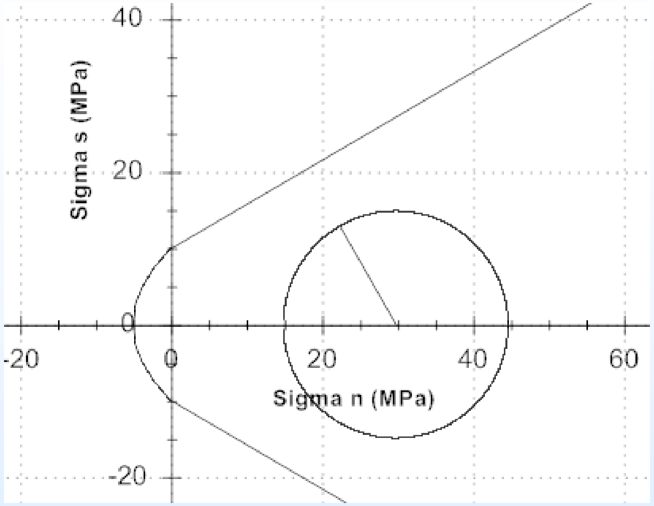
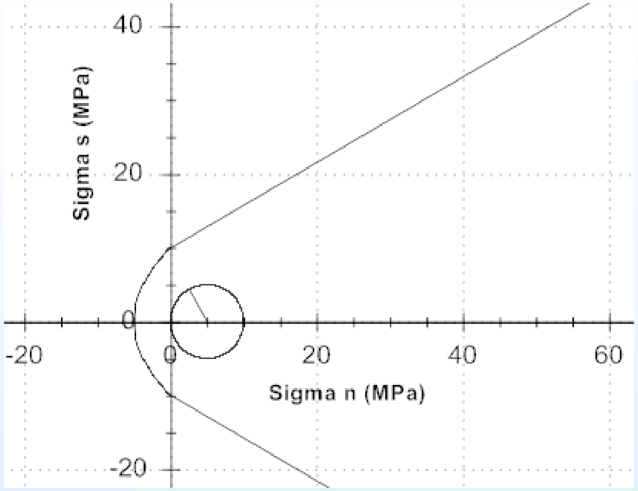
(Gutierrez, Øino and Nygaard 2000)

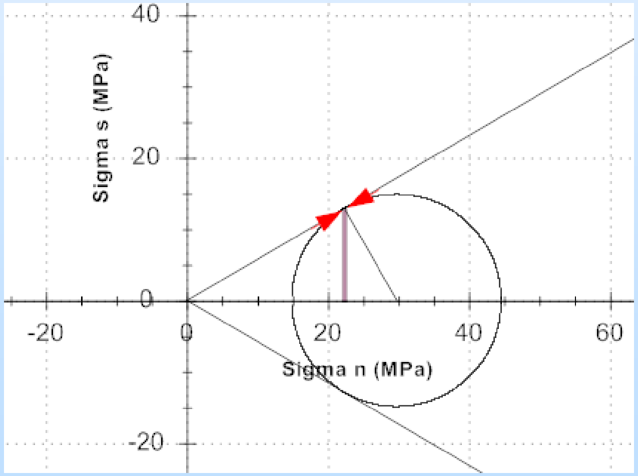
Fracture Formation / Reactivation



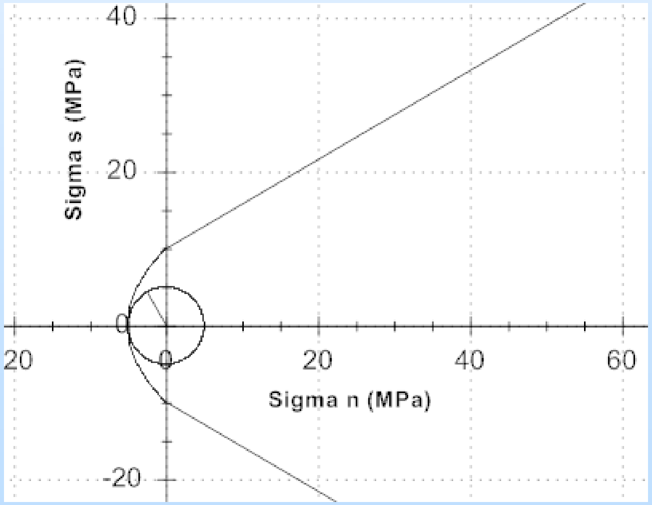
Safe State of Stress



Safe State of Stress



Fracture Reactivation



Tensile Failure

Seismicity Prediction

- Seismic Moment:

  M_0=G*A*D

  Kanamori and Anderson (1975)

  G: Shear modulus (dyne/cm^2)

  A: Rupture area (cm^2)

  D: Average fault slip (cm)

- Resulting Earthquake:

Steing and Wysession 2003

$$M_W = \frac{\log(M_0)}{1.5} - 10.73$$

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Parameter Calculation(Isothermal)

After Inoue and Fontoura 2009

$$\emptyset^{n+1} = \emptyset^n + \alpha(\varepsilon_v^{n+1} - \varepsilon_v^n) + \frac{1}{Q}(P^{n+1} - P^n)$$

ϕ^n is the existing porosity, at pore pressure P^n and volumetric strain ε_v^n

ϕ^{n+1} is the new porosity resulting from the new pore pressure, P^{n+1} and the new volumetric strain ε_v^{n+1}.

Q, the Biot parameter, is defined as: $$Q = \frac{1}{C_f \emptyset^n + C_s(\alpha - \emptyset^n)}$$

C_f is the compressibility of the fluid, C_S is the compressibility of the rock and the Biot coefficient, α,

K_S : Saturated Matrix Bulk Modulus

$$\alpha = 1 - \frac{K_D}{K_S}$$

K_D : Drained Bulk Modulus

$$K_S = \frac{E_S}{3(1 - 2v_S)}$$

$$K_D = \frac{E_D}{3(1 - 2v_D)}$$

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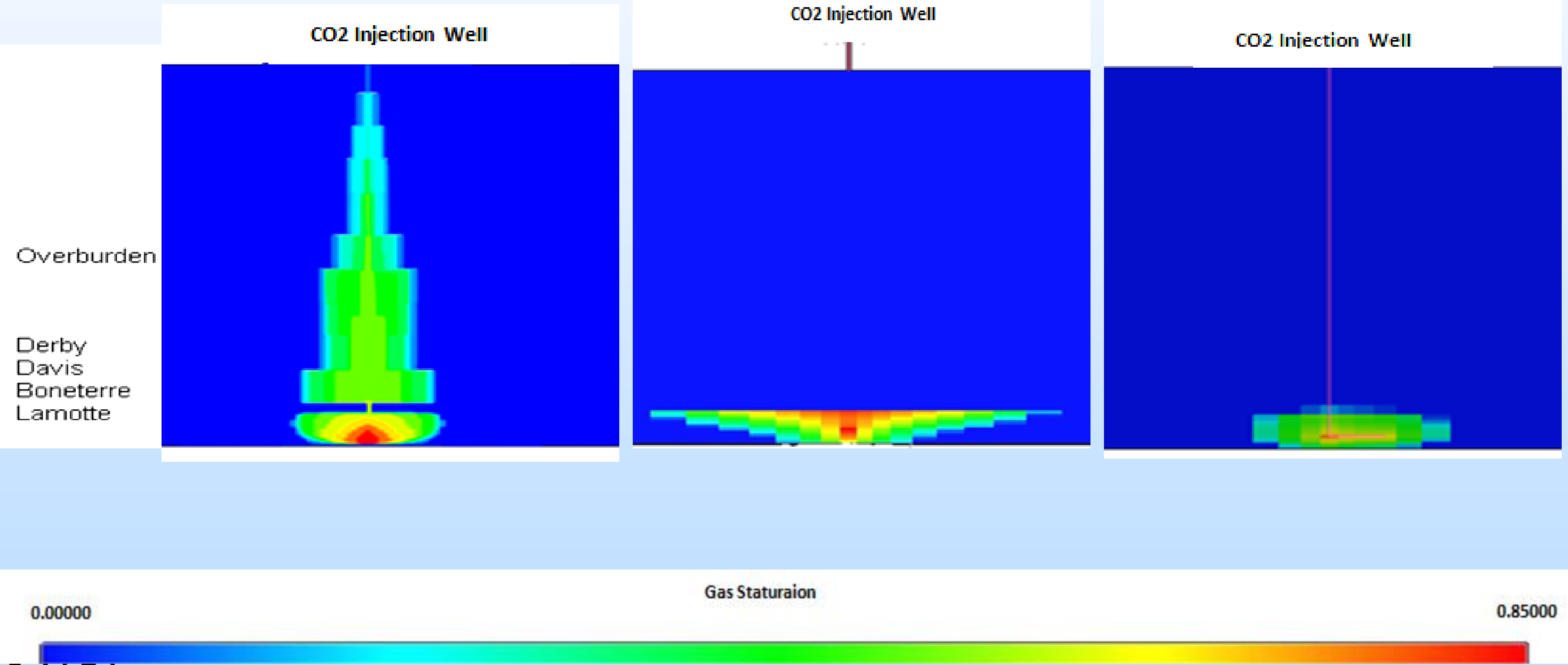
After 25 years in the closed reservoir at injection rate of 10 tons/day

Caprock Penetrating Fracture

Without Incorporation of Geomechanics

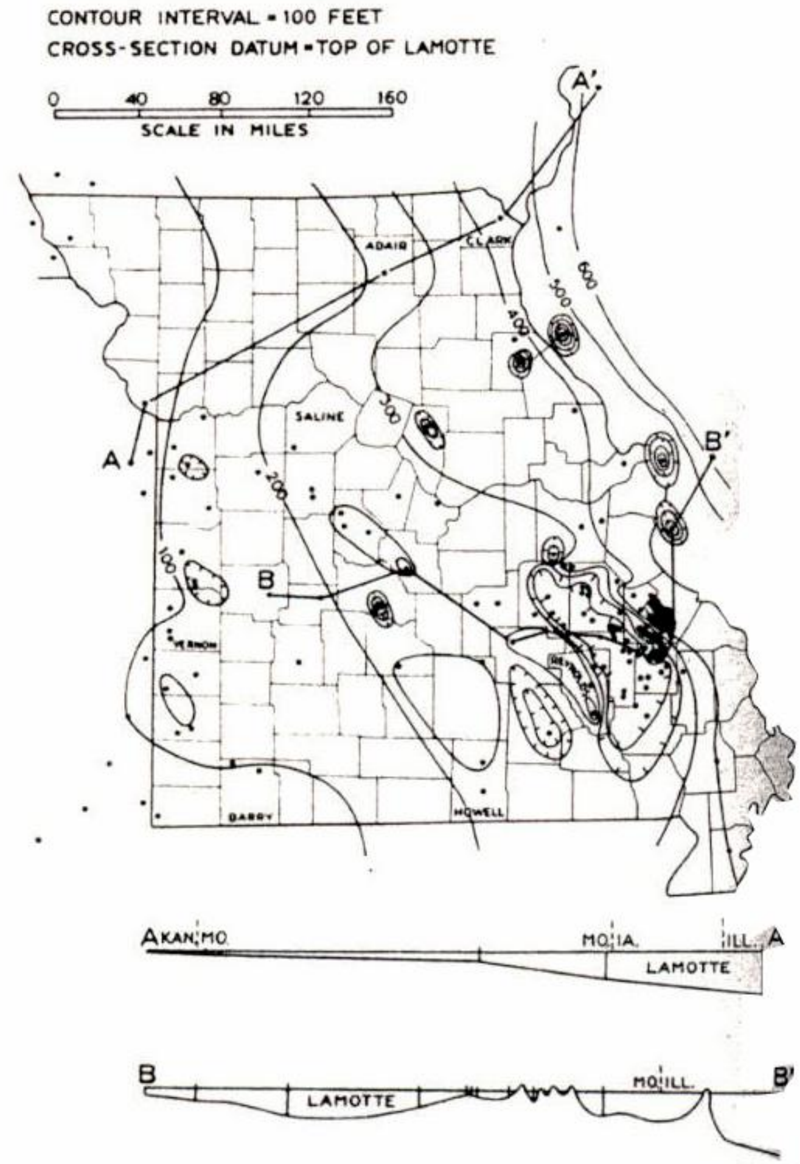
Horizontal Well



LaMotte Sandstone Evaluation

Isopach Map (formation thickness) of Lamotte Formation across Missouri

Equivalent basal sandstone in Illinois are referred to as the Mount Simon Formation



Source: Ojakangas, 1963

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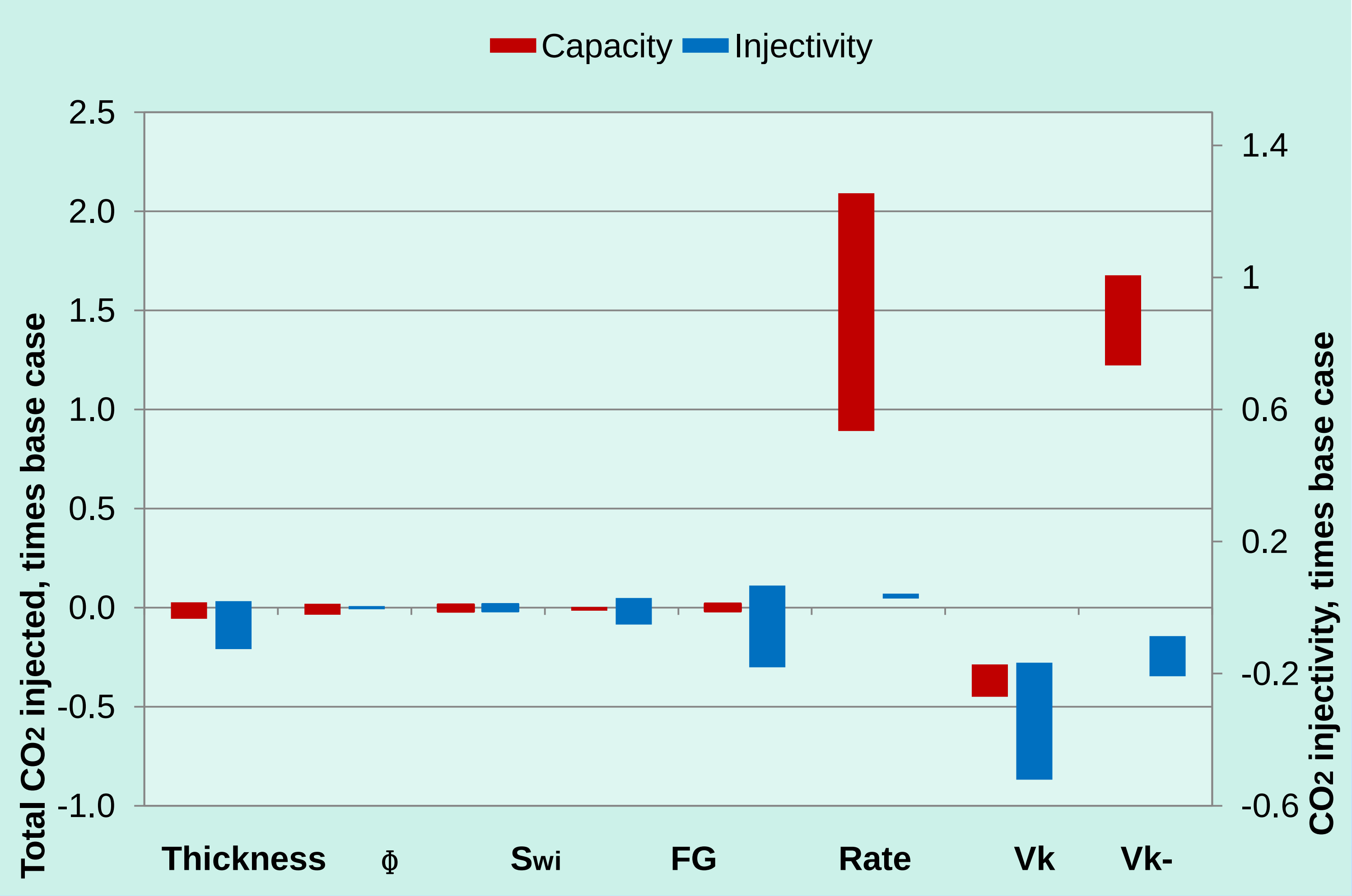
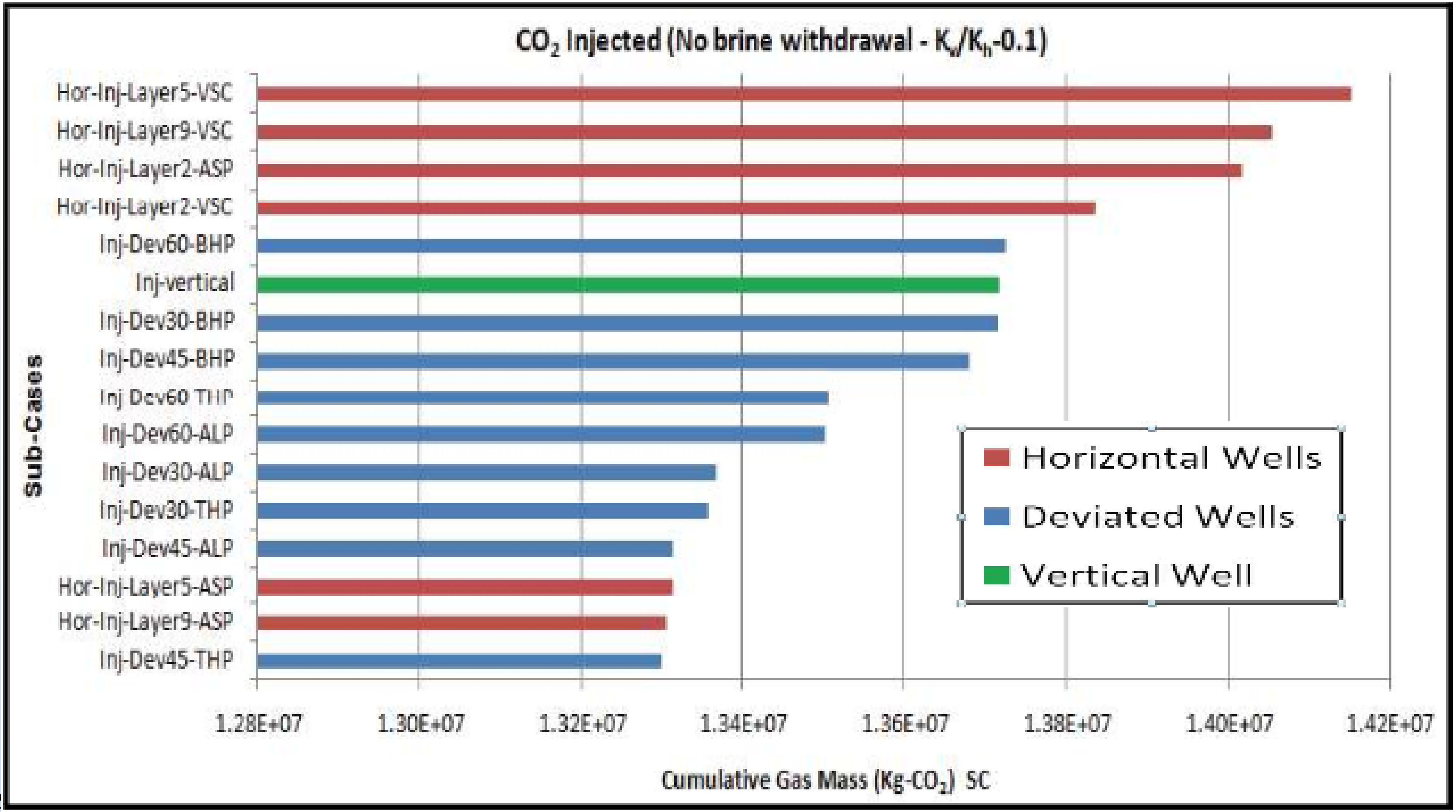
Factors controlling CO_2 storage capacity and injectivity



Injection well placement



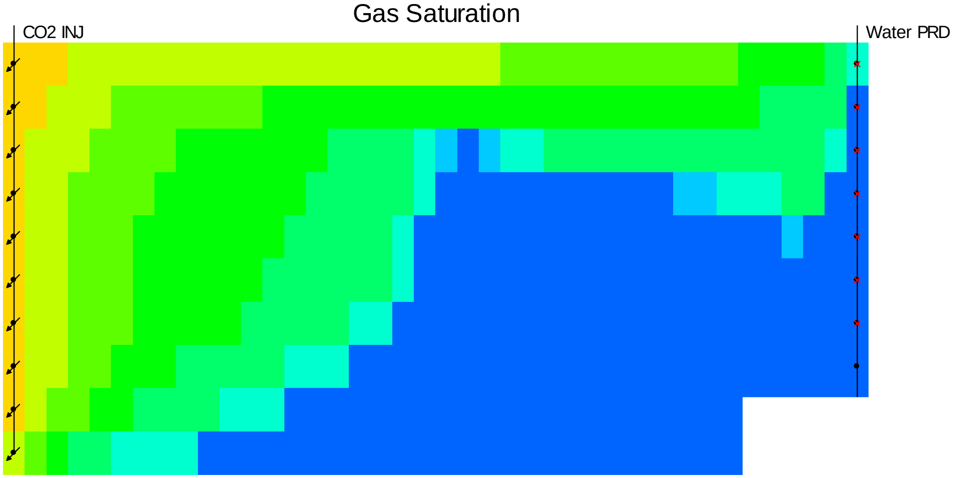
Water withdrawal break through time controlled by vertical permeability

Base water withdrawal Breakthrough: 13 yrs

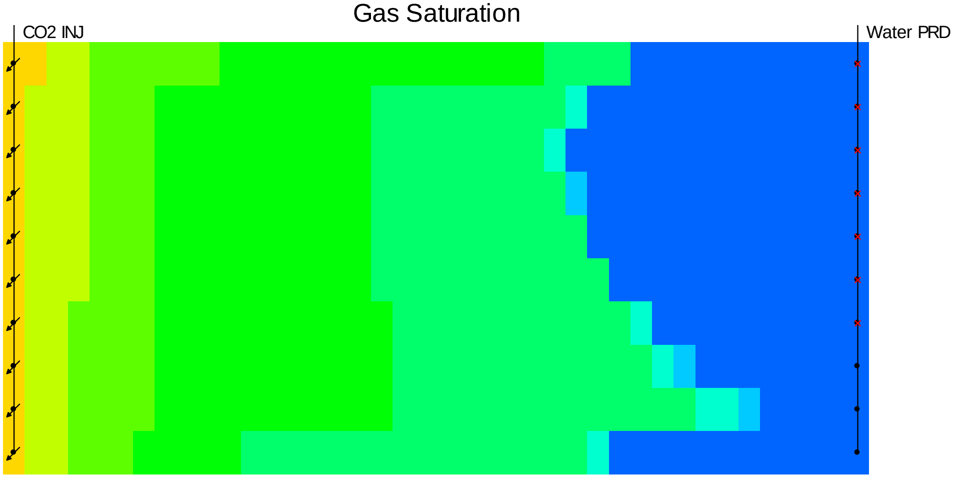
Gas Saturation

… and vertical to horizontal permeability ratio

Kv/Kh=0.1 Breakthrough: 31 yrs



Kv/Kh=0.01 Breakthrough: 44 yrs



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