THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

EASiTool 3.0

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GULF COAST CARBON CENTER

Outline

- What is EASiTool?
- Assumptions and limitations
- Technical background
- Interface
  - Input
  - output
- Case study
- Time-lapse compressibility monitoring

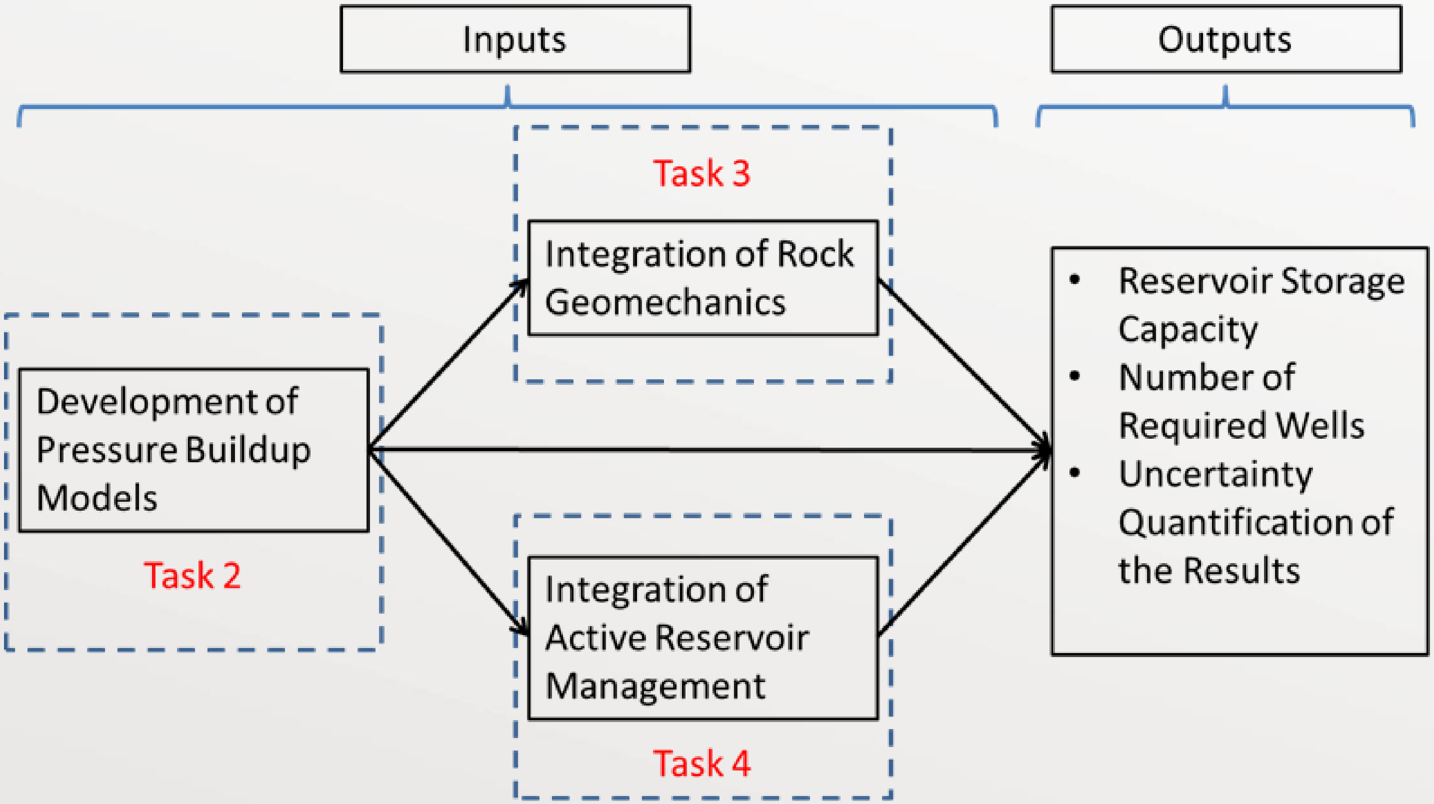
Enhanced Analytical Simulation Tool for CO_2 storage capacity Estimation (EASiTool)

- Funded by Department of Energy (2013-2018)
- It uses analytical models to estimate the storage capacity.
  - It does sensitivity analysis
  - It provides the number of injection wells required
  - It integrates some geomechanical aspects
  - It does a simple NPV analysis

Methods Comparison

Tool/Approach Name	DOE/NETL	CSLF	USGS	EASiTool	Numerical Simulators
Reservoir scale	Yes	Yes	Yes	Yes	Yes
Accuracy	Low	Low	Low	Medium/High	High
Boundary conditions	No	No	No	Yes	Yes
Rock geomechanics	No	No	No	Yes*	Yes
Brine management	No	No	No	Yes	Yes
Required expertise	Low	Low	Low	Low	High
Cost of use	Low	Low	Low	Low	High
Computational speed	High	High	High	High	Low
Dynamic	No	No	No	Yes	Yes
Sensitivity Analysis	Simple	Simple	Simple	Yes	Yes

EASiTool overview



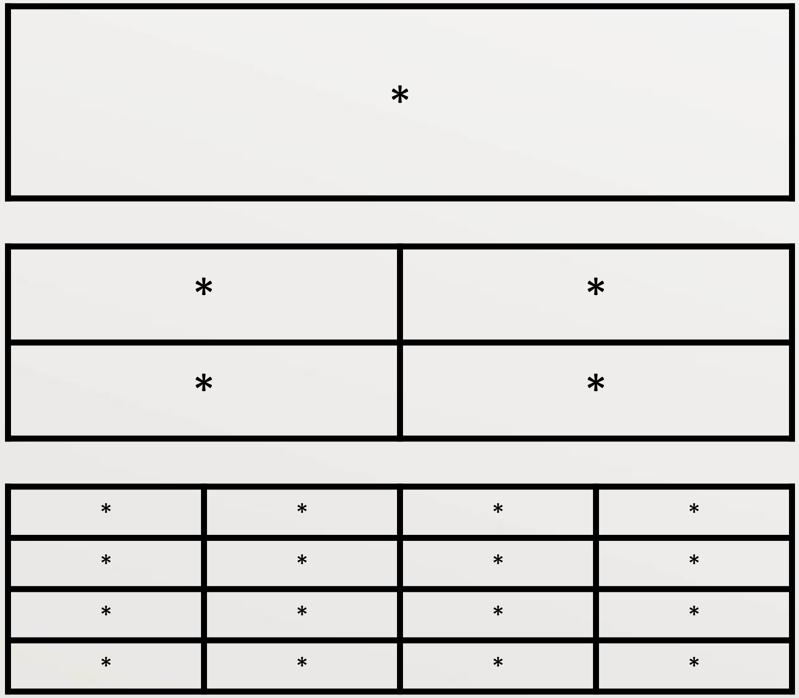
Technical Elements

- Developing superposition theory for multi-well CO_2 injection
- Solving for both open and closed boundary conditions
- Considering brine evaporation and salt precipitation
- Finding injection rates to max. storage capacity (inverse problem)
- Analytical estimating of maximum allowable injection pressure
    - ✓ Stress-pore pressure coupling
    - ✓ Thermal stress

1 well

4 well

16 well

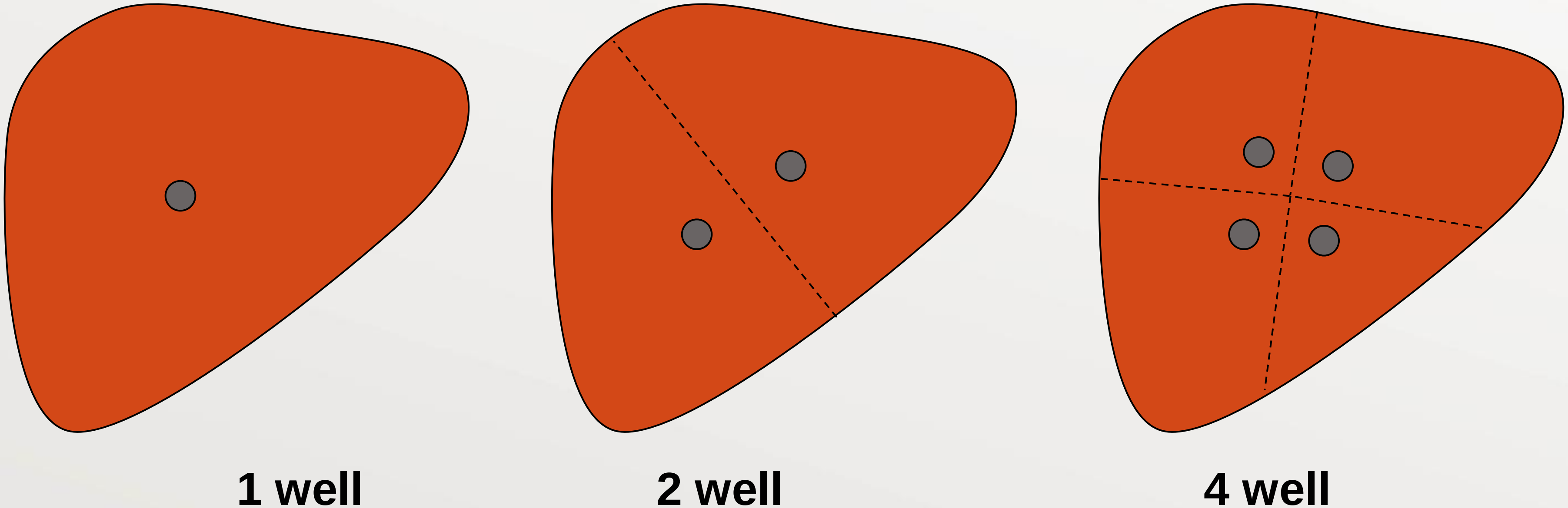


Assumptions

- Homogeneous/isotropic properties
- Constant rate injection
- No specific structure
- Two-phase flow (Brine and CO_2)
- Fluid properties are pressure dependent
- Use superposition for multiwell scenarios

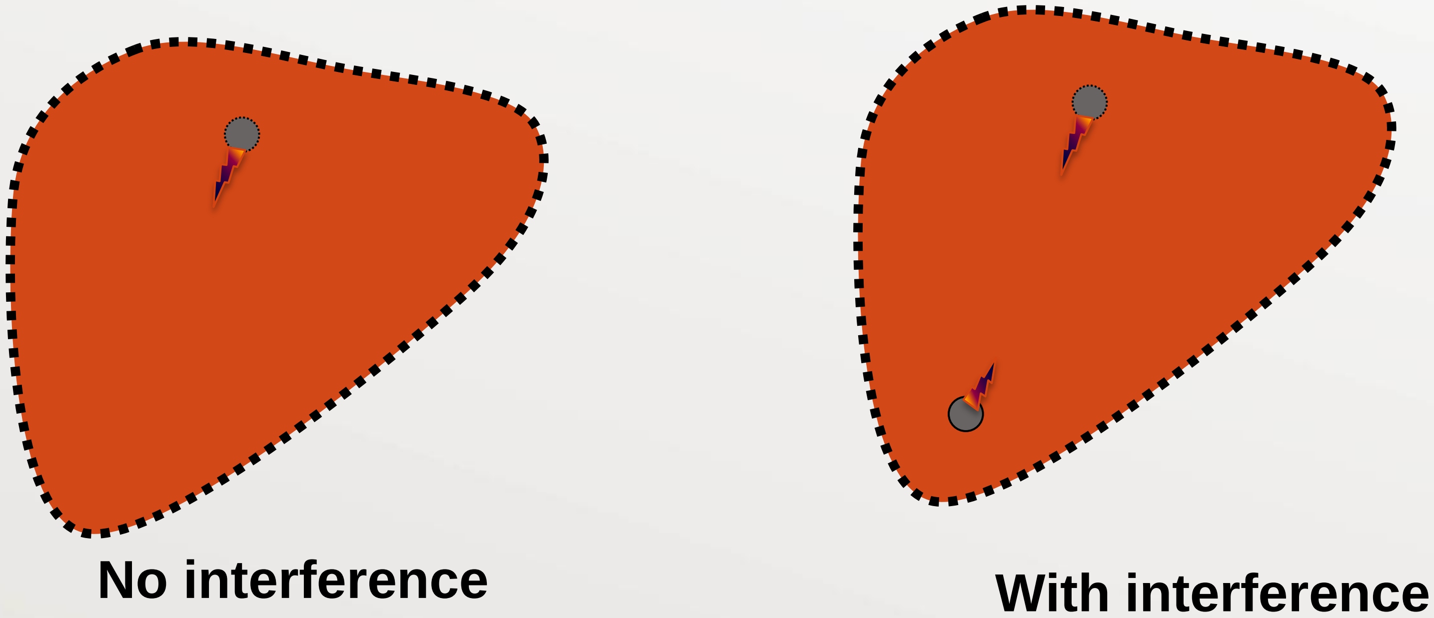
Superposition (multi-well injection)

- Good news: multiple injectors enable greater overall injection rate than single well
- Bad news: multiple injectors interfere with each other



Superposition (multi-well injection)

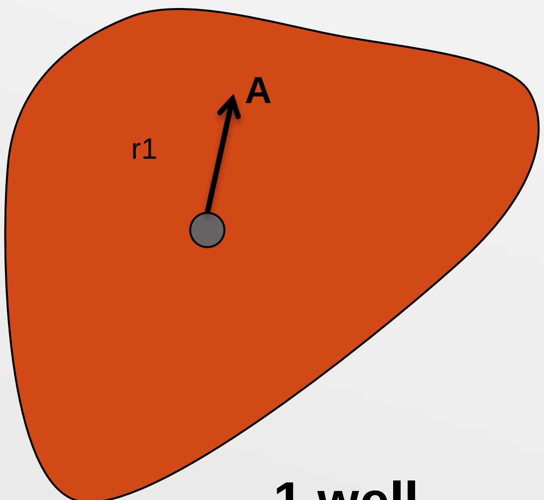
- **Interference vs. no interference**



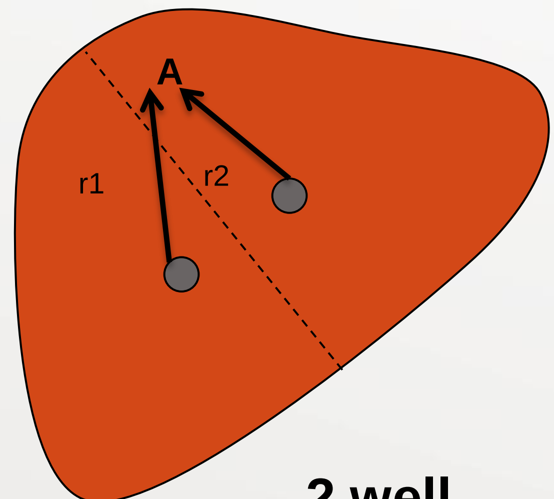
Superposition (multi-well injection)

P_A=f(reservoir and fluid prop.,r1,t)

$P_A=P_{r1}+P_{r2}$



1 well



2 well

Water Resources Research
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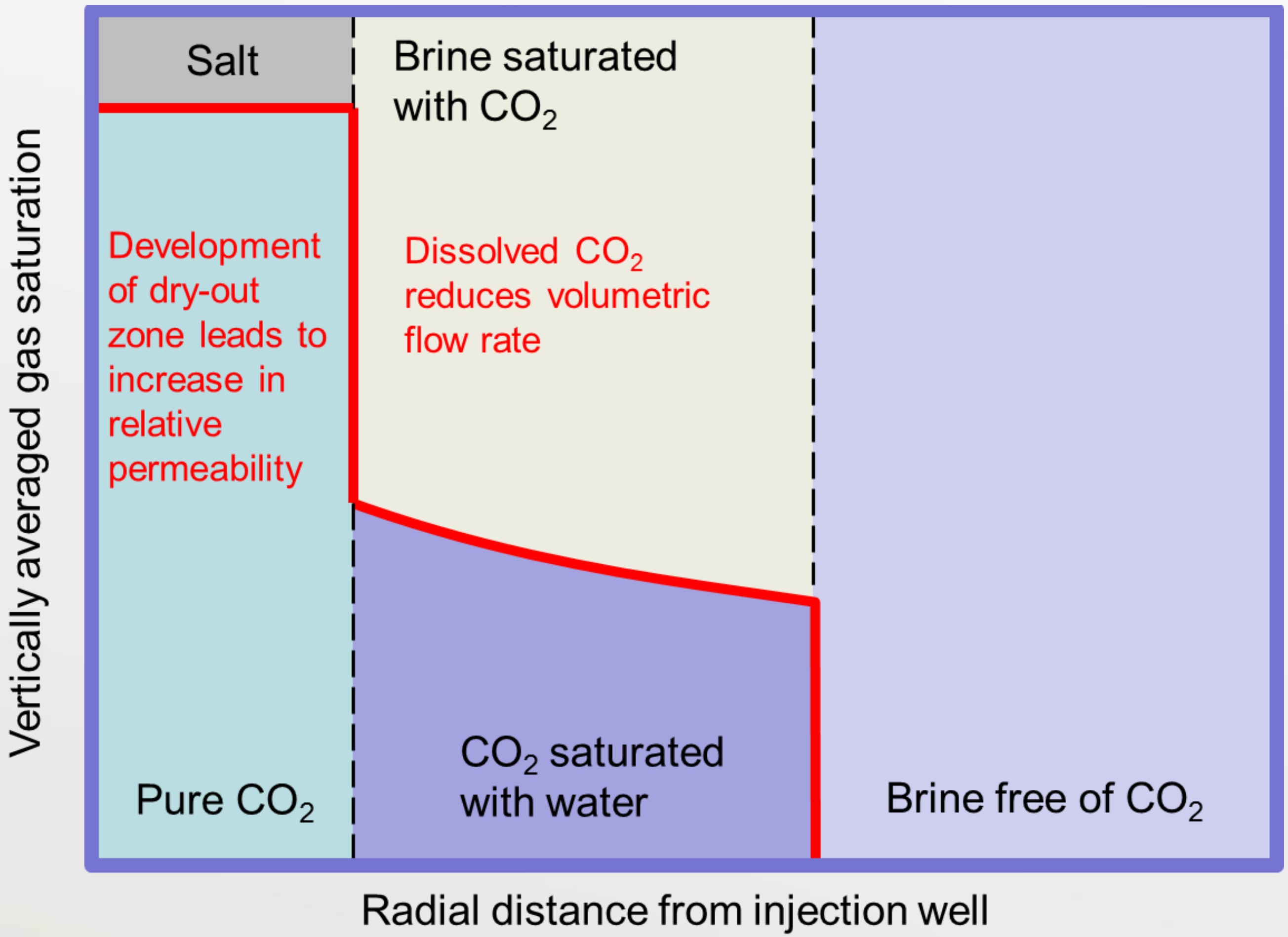
Regular Article

Role of partial miscibility on pressure buildup due to constant rate injection of CO_2 into closed and open brine aquifers

Simon A. Mathias, Jon G. Gluyas, Gerardo J. González Martínez de Miguel, Seyyed A. Hosseini

Analytical model



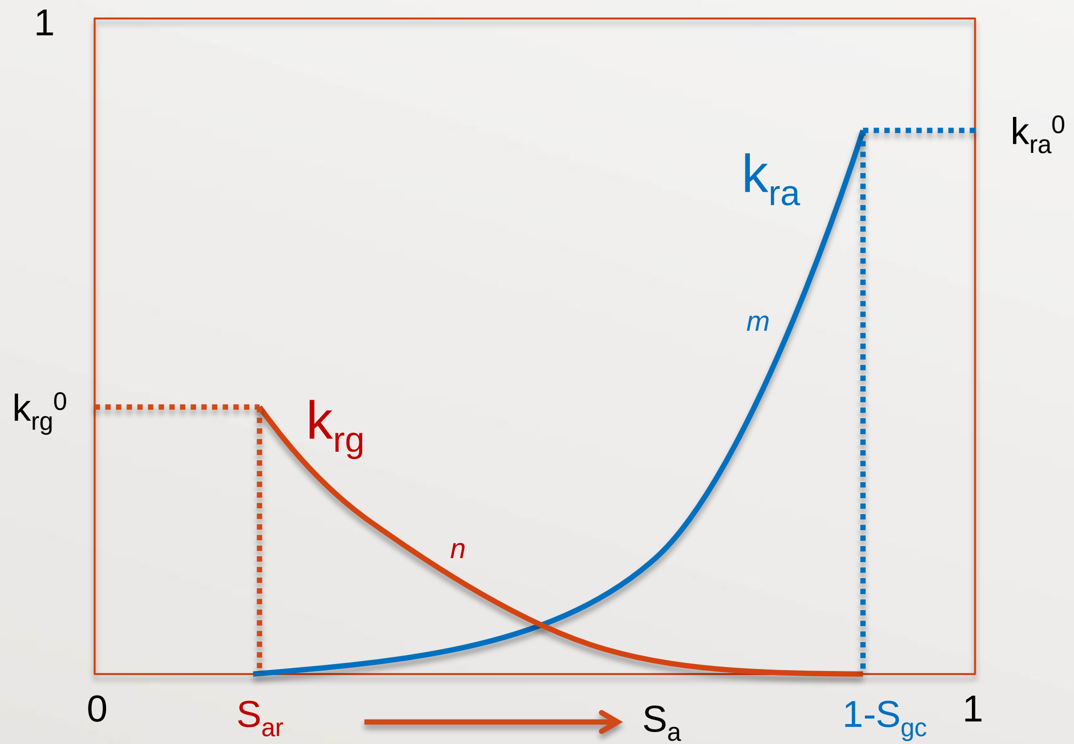
Relative Permeability (two-phase flow)

- Brooks-Corey model:

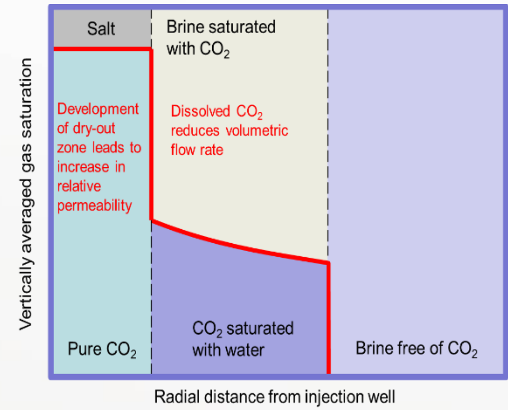
$$k_{rg} = \begin{cases} 0, & S_g < S_{gc} \\ k_{rg}^{\circ}\left(\dfrac{S_g - S_{gc}}{1 - S_{ar} - S_{gc}}\right)^n, & S_g > S_{gc} \end{cases}$$

$$k_{ra} = \begin{cases} 0, & S_a < S_{ar} \\ k_{ra}^{\circ}\left(\dfrac{S_a - S_{ar}}{1 - S_{ar} - S_{gc}}\right)^m, & S_a > S_{ar} \end{cases}$$

$S_g=1-S_a$



Analytical model

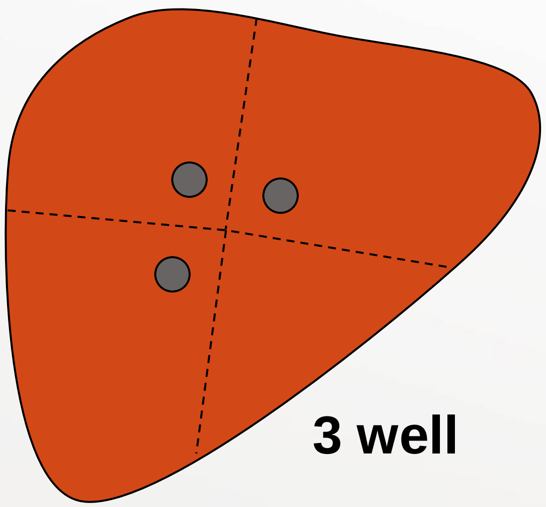


$$P - P_0 =$$

$$\frac{M_0}{4\pi\rho_c Hk}\begin{cases} \dfrac{\mu_c q_{D1}}{k_{rs}} \ln\left(\dfrac{z_T}{z}\right) + \mu_g q_{D2} F_2(z_T) + \mu_b q_{D3} F_1(z_L), & 0 \leq z < z_T \\[2em] \mu_g q_{D2} F_2(z) + \mu_b q_{D3} F_1(z_L), & z_T \leq z \leq z_L \\[2em] \mu_b q_{D3} F_1(z), & z > z_L, \end{cases}$$

Superposition (multi-well injection)

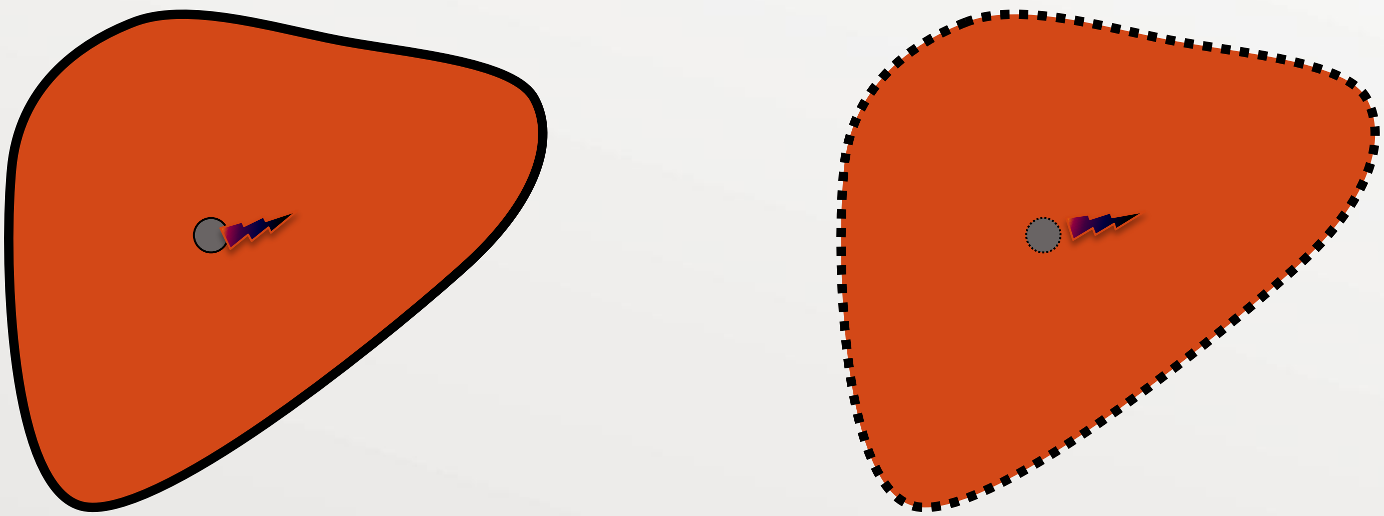
- Finding the optimized rate to maximize storage capacity



$$\begin{bmatrix} \frac{1}{2}\left(\ln(t_D)+0.80908\right)+S_a & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\lambda_w}}E_i\left(-\frac{r_{D1-2}^2}{4\eta_{D3}t_D}\right) & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\lambda_w}}E_i\left(-\frac{r_{D1-3}^2}{4\eta_{D3}t_D}\right) \\ -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\lambda_w}}E_i\left(-\frac{r_{D2-1}^2}{4\eta_{D3}t_D}\right) & \frac{1}{2}\left(\ln(t_D)+0.80908\right)+S_a & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\lambda_w}}E_i\left(-\frac{r_{D2-3}^2}{4\eta_{D3}t_D}\right) \\ -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\lambda_w}}E_i\left(-\frac{r_{D3-1}^2}{4\eta_{D3}t_D}\right) & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\lambda_w}}E_i\left(-\frac{r_{D3-2}^2}{4\eta_{D3}t_D}\right) & \frac{1}{2}\left(\ln(t_D)+0.80908\right)+S_a \end{bmatrix} \begin{Bmatrix} q^1 \\ q^2 \\ q^3 \end{Bmatrix} = \begin{Bmatrix} \frac{2\pi hk\overline{k_{rg}}}{\mu_g}\Delta P \\ \frac{2\pi hk\overline{k_{rg}}}{\mu_g}\Delta P \\ \frac{2\pi hk\overline{k_{rg}}}{\mu_g}\Delta P \end{Bmatrix}$$

Boundary Condition

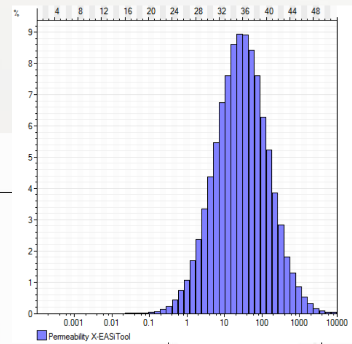
- Open vs. Closed

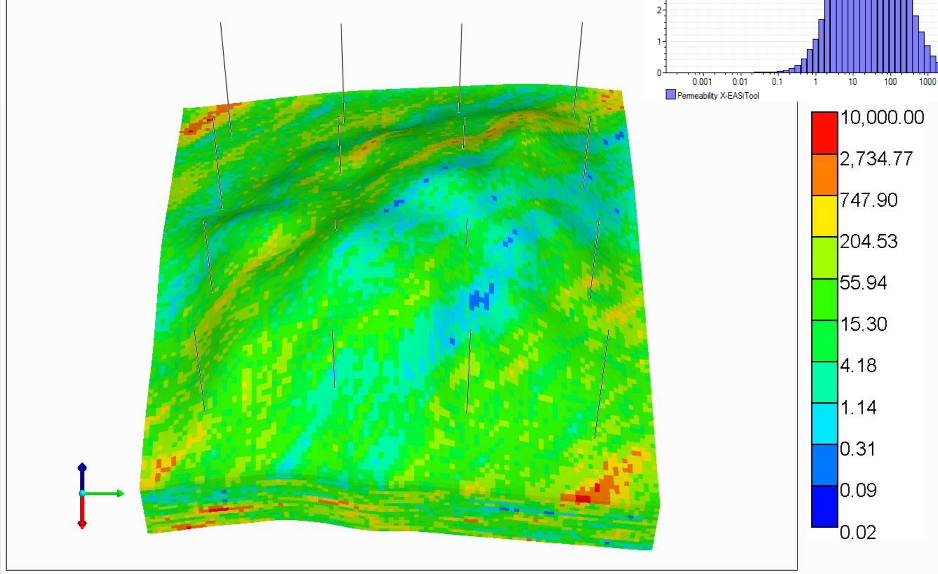


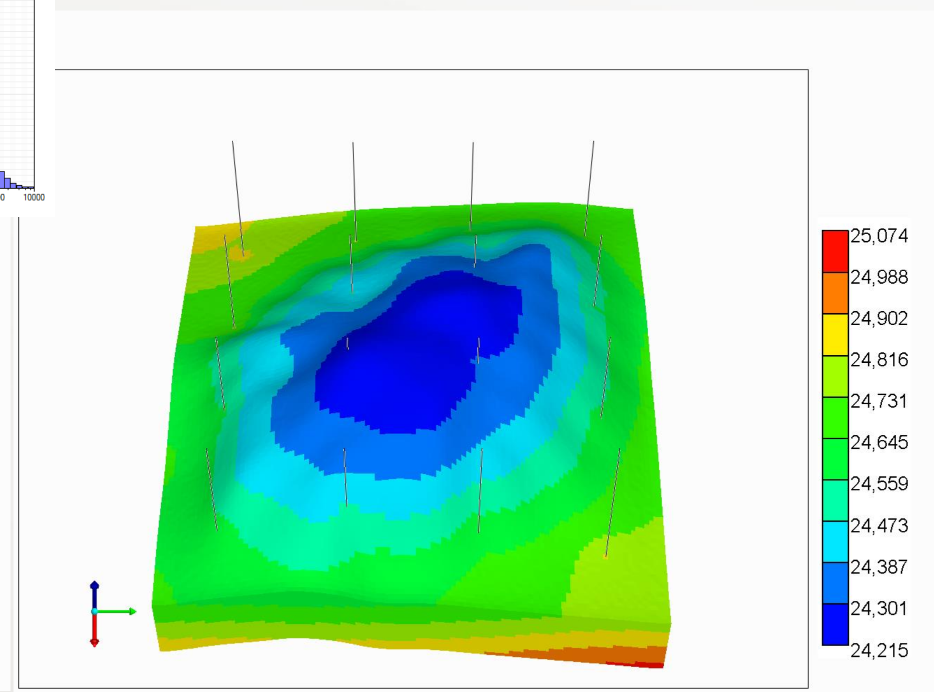
Closed

Open

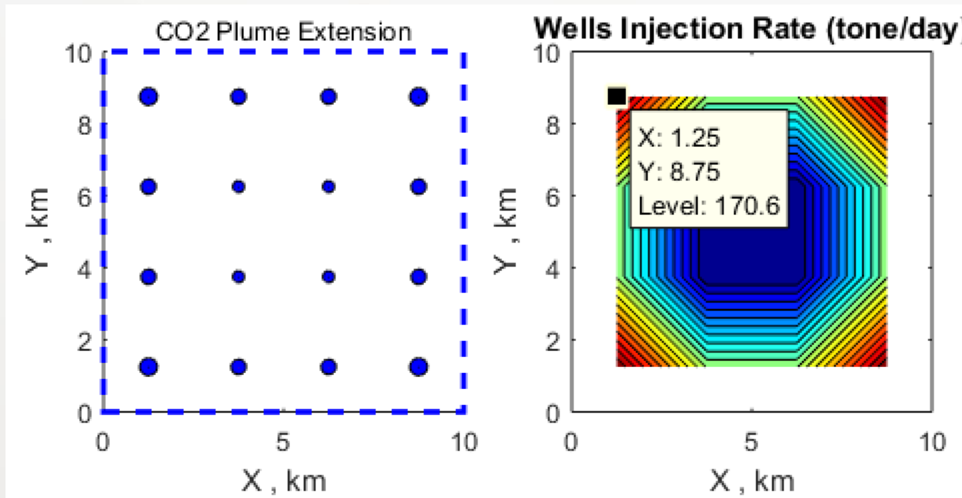
Verification of EASiTool Models

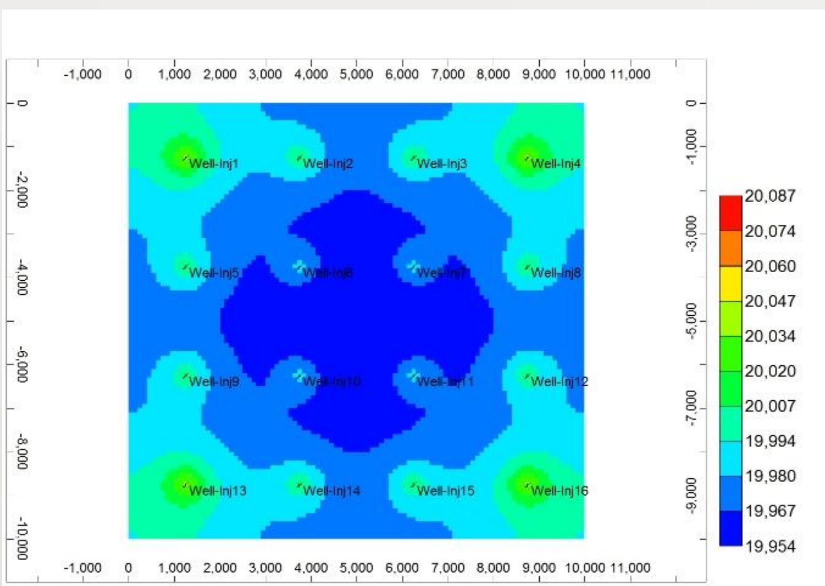


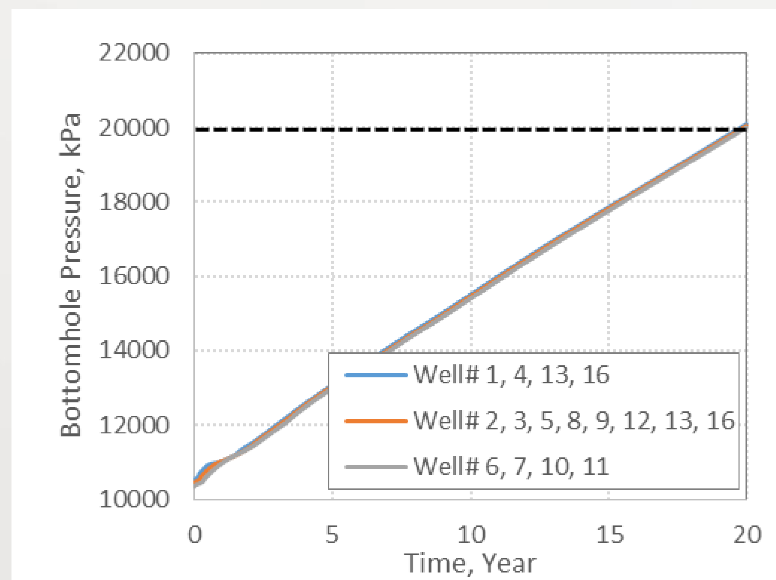




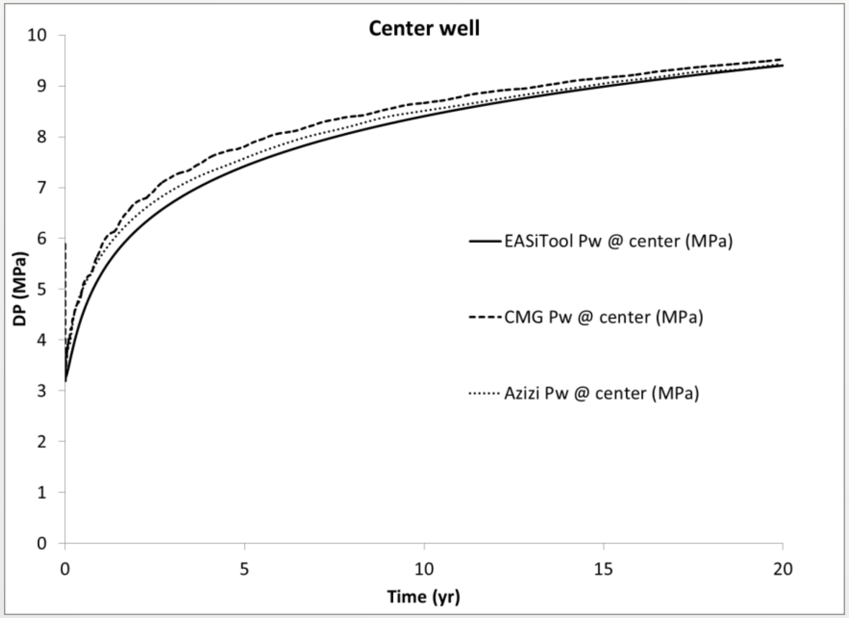
Verification of EASiTool Models

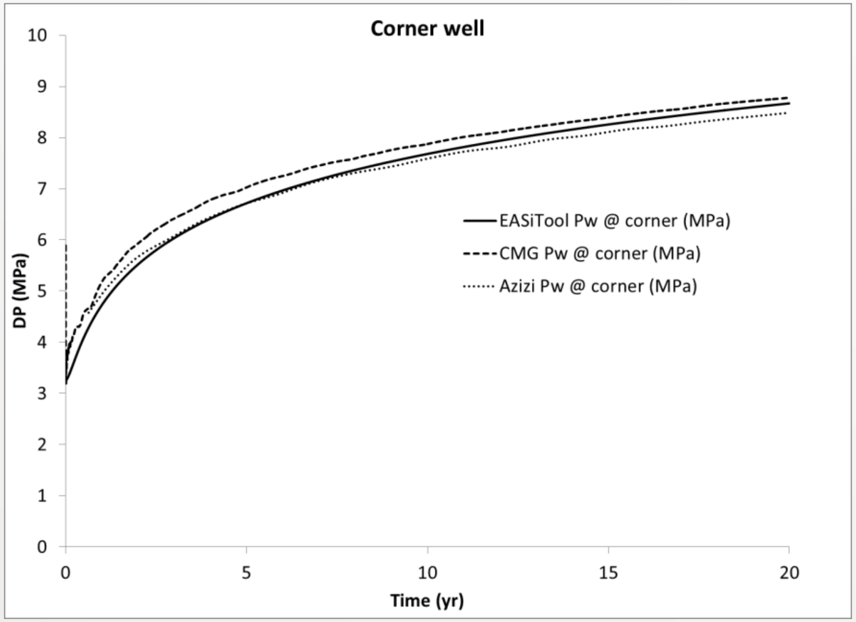


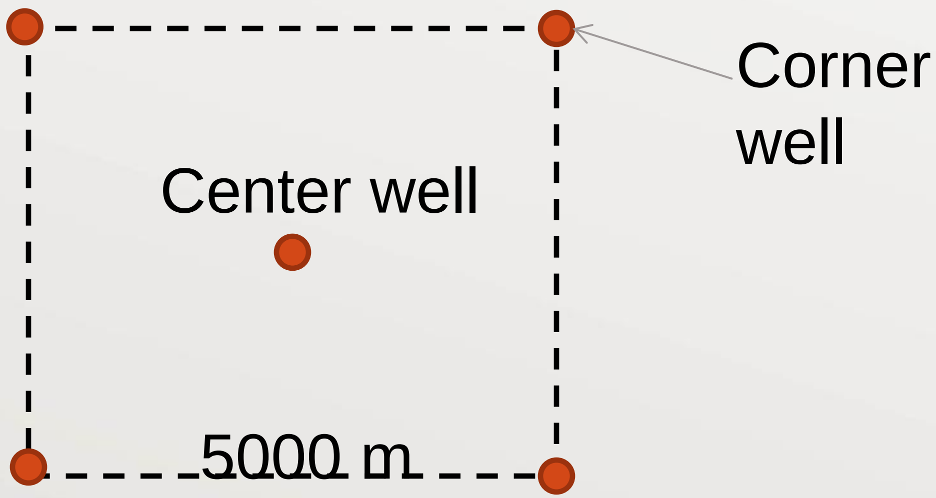




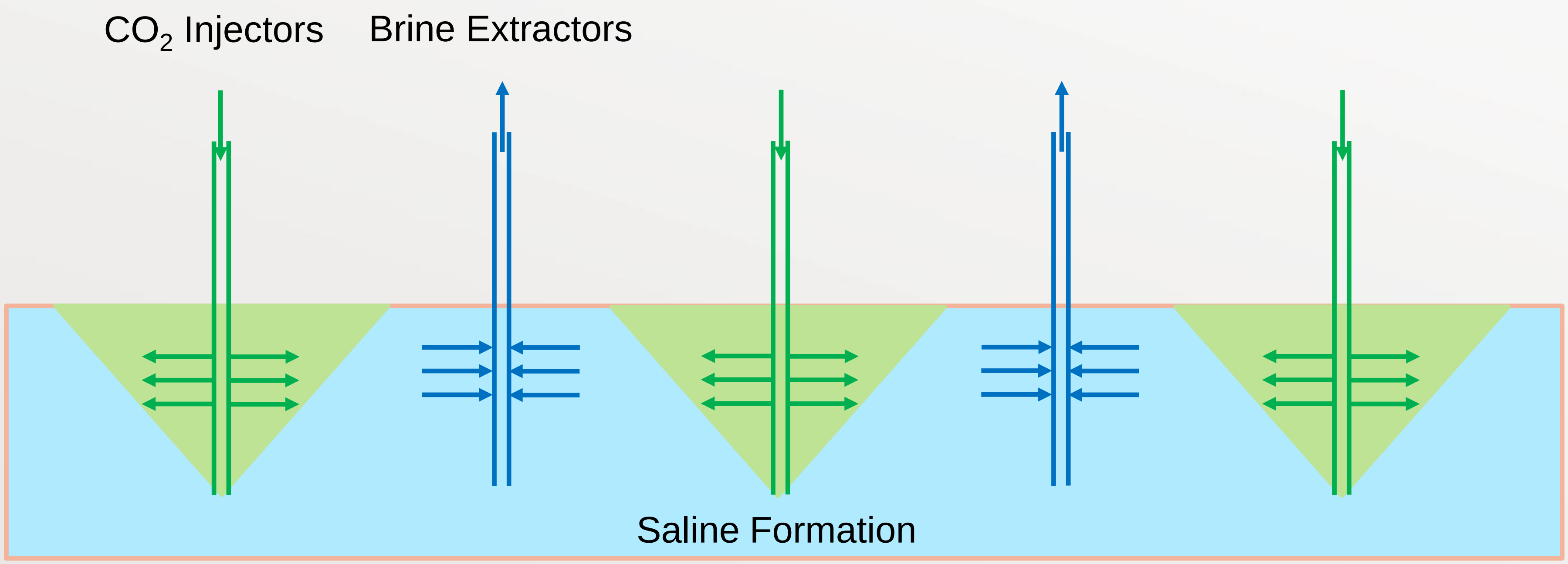
Progress to Date on Key Technical Issues





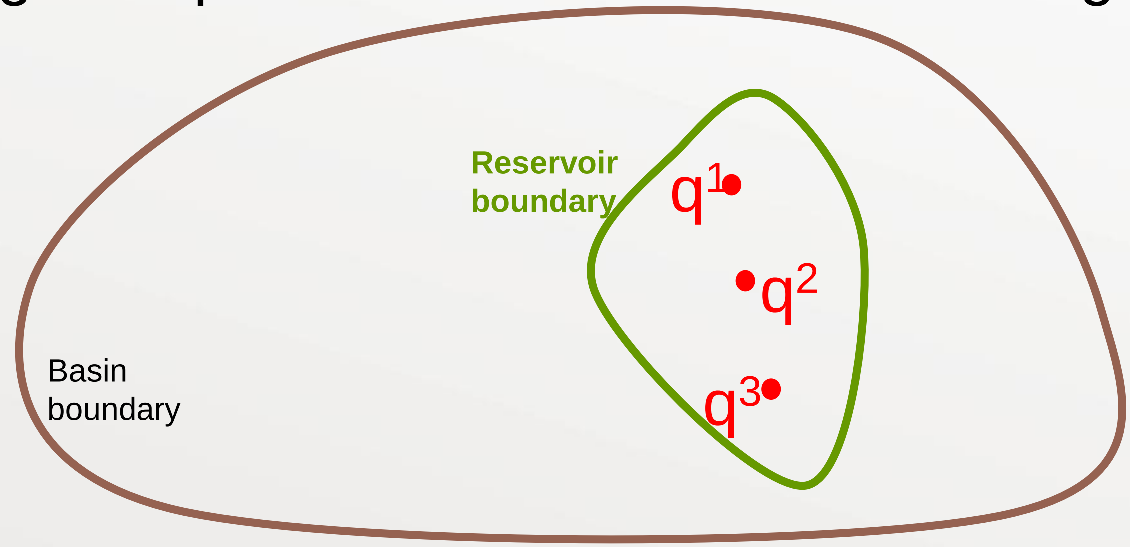


Brine Extraction



Brine Extraction Theory

- Finding the optimized rate to maximize storage capacity



$$\begin{bmatrix} \frac{1}{2}\left(\ln(t_D)+0.80908\right)+S_a & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\overline{\lambda_w}}}E_i\left(-\frac{r_{D1-2}^2}{4\eta_{D3}t_D}\right) & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\overline{\lambda_w}}}E_i\left(-\frac{r_{D1-3}^2}{4\eta_{D3}t_D}\right) \\ -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\overline{\lambda_w}}}E_i\left(-\frac{r_{D2-1}^2}{4\eta_{D3}t_D}\right) & \frac{1}{2}\left(\ln(t_D)+0.80908\right)+S_a & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\overline{\lambda_w}}}E_i\left(-\frac{r_{D2-3}^2}{4\eta_{D3}t_D}\right) \\ -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\overline{\lambda_w}}}E_i\left(-\frac{r_{D3-1}^2}{4\eta_{D3}t_D}\right) & -\frac{1}{2}\frac{\overline{\lambda_g}}{\overline{\overline{\lambda_w}}}E_i\left(-\frac{r_{D3-2}^2}{4\eta_{D3}t_D}\right) & \frac{1}{2}\left(\ln(t_D)+0.80908\right)+S_a \end{bmatrix} \begin{Bmatrix} q^1 \\ q^2 \\ q^3 \end{Bmatrix} = \begin{Bmatrix} \frac{2\pi hk\overline{k_{rg}}}{\underline{\mu_g}}\Delta P_{\max} \\ \frac{2\pi hk\overline{k_{rg}}}{\underline{\mu_g}}\Delta P_{\max} \\ \frac{2\pi hk\overline{k_{rg}}}{\mu_g}\Delta P_{\max} \end{Bmatrix}$$

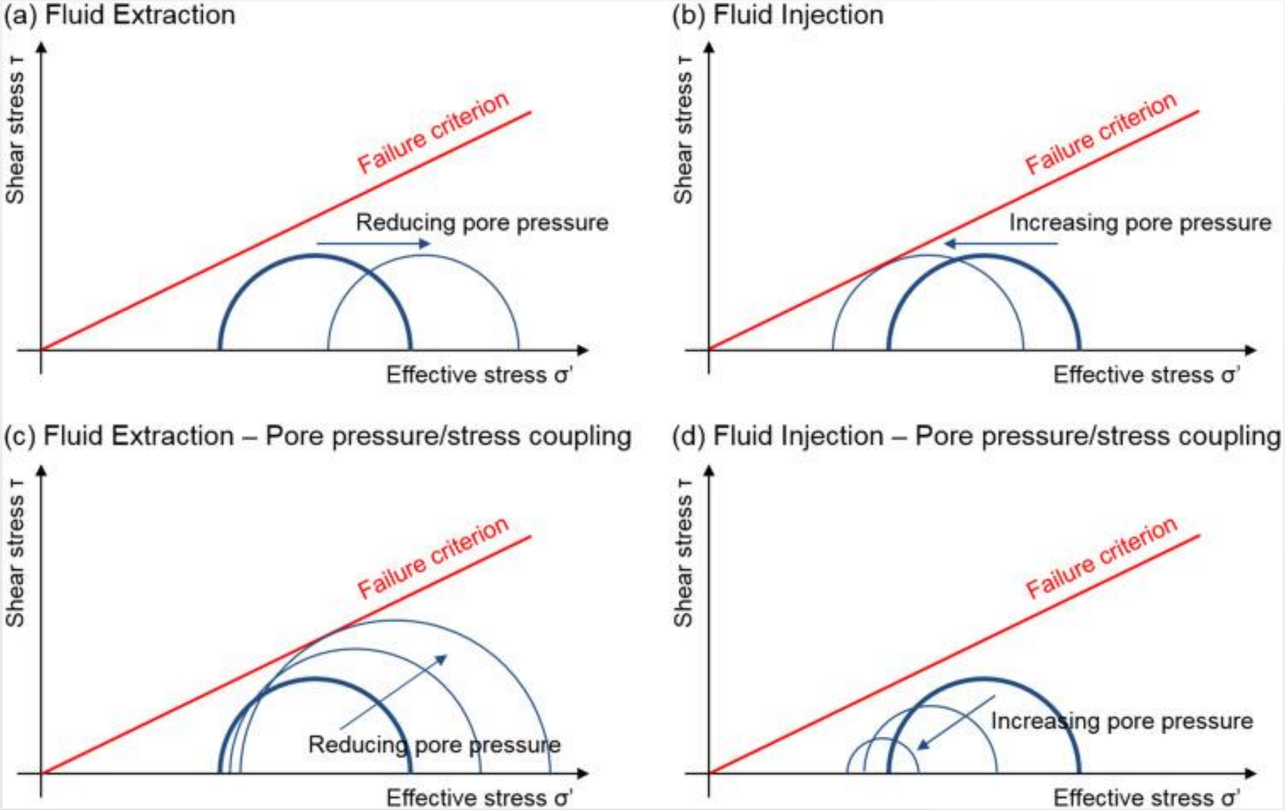
Maximum injection pressure

- Pore pressure stress coupling
  - Change in total stress ($\Delta\sigma$)is coupled with change in pore pressure(ΔP).
  - We define $\beta_h = \Delta\sigma_h / \Delta P$ and $\beta_v = \Delta\sigma_v / \Delta P$ & typically $\beta_h > \beta_v$
- Thermal stress
  - Injected CO_2 is generally colder than formation brine.
  - shrinkage of the rock formation (specially near the injection well) by $\sigma^{\Delta T} = 2\alpha_T E \Delta T / (1-2\vartheta)$
- Mohr-Coulomb shear failure criterion

$$\tau = c + (\sigma_n - \alpha \cdot P_{max})\mu$$

Kim, S, and Hosseini, S. A., 2014, Geological CO_2 storage: incorporation of pore-pressure/stress coupling and thermal effects to determine maximum sustainable pressure limit: Energy Procedia, v. 63, p. 3339-3346, http://doi.org/10.1016/j.egypro.2014.11.362.

Shear Slip


(a) Fluid Extraction
Shear stress τ
Failure criterion
Reducing pore pressure
Effective stress σ'
(b) Fluid Injection
Shear stress τ
Failure criterion
Increasing pore pressure
Effective stress σ'
(c) Fluid Extraction – Pore pressure/stress coupling
Shear stress τ
Failure criterion
Reducing pore pressure
Effective stress σ'
(d) Fluid Injection – Pore pressure/stress coupling
Shear stress τ
Failure criterion
Increasing pore pressure
Effective stress σ'

Thermal Stress in EASiTool

- CO_2 injection: volume expansion and increase in stress driven by fluid injection
- But injecting colder fluid will also cause thermal contraction and decrease in stress
- If temperature drops by ΔT, total stress decreases as follows (assuming fully constrained sediment):

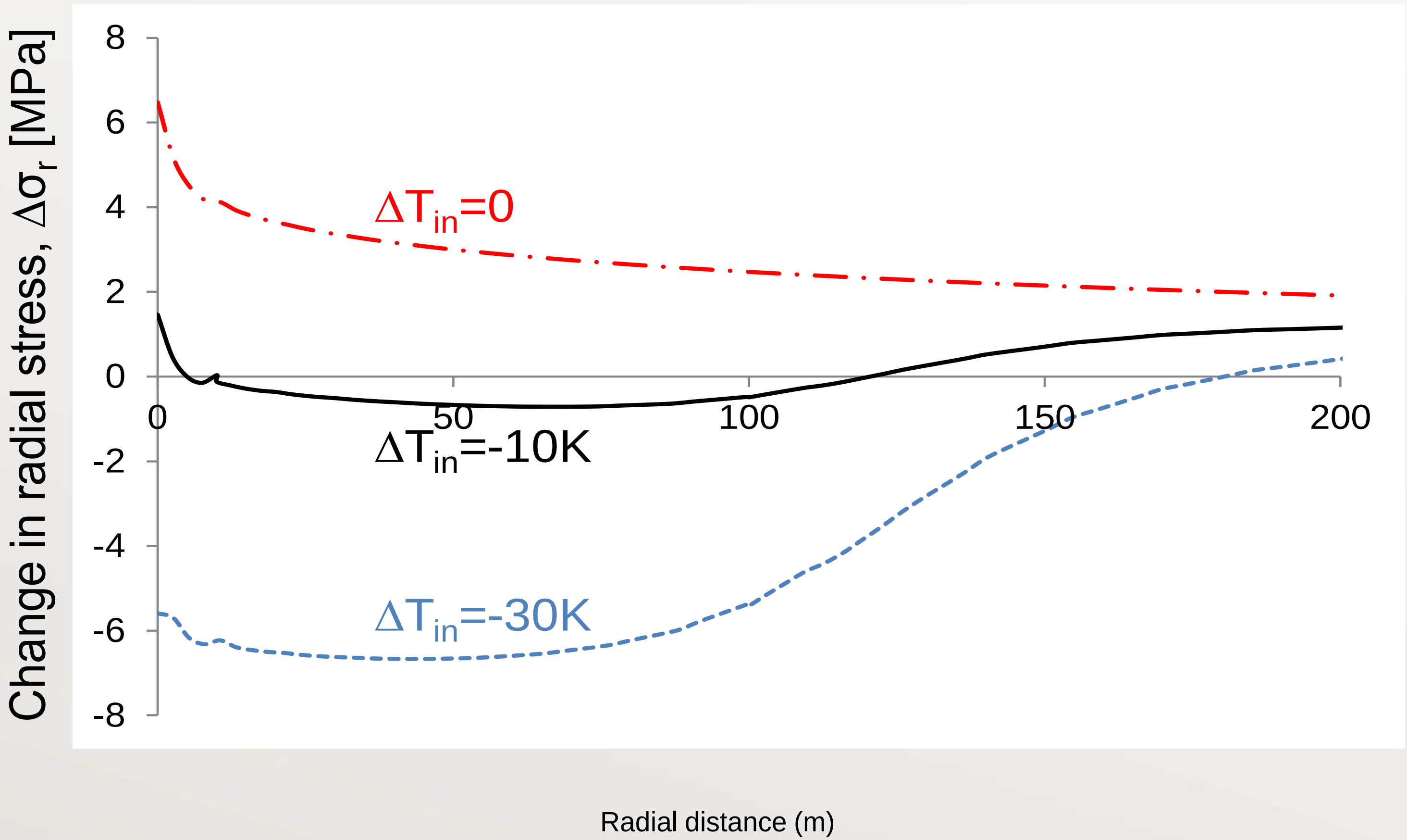
$$\Delta\sigma^T = \frac{\alpha_T E \Delta T}{1-2\nu}$$

αT: coefficient of thermal expansion and E: Young's modulus

- We developed analytical solution to estimate P_{max} under Normal-Faulting and Reverse-Faulting and integrated into our capacity estimation module.

Thermal Effects

- Increase in the total stress from the poroelastic effect
- Decrease in the total stress from the thermal effect



Maximum injection pressure

- Normal fault system

$$P_{\max} = \frac{1}{\left[2\alpha - \beta_v - \beta_h - (\beta_v - \beta_h)\cos 2\theta + (\beta_v - \beta_h)\sin 2\theta / \mu\right]} \cdot$$
$$\left[\{(1+K) + (1-K)\cos 2\theta - (1-K)\sin 2\theta/\mu\}\sigma_{v0} - \{(\beta_v + \beta_h) + (\beta_v - \beta_h)\cos 2\theta - (\beta_v - \beta_h)\sin 2\theta/\mu\}P_{pi} - \frac{2\alpha_T E\Delta T}{1-2\nu}\right]$$

- Reverse fault system

$$P_{\max} = \frac{1}{\left[2\alpha - \beta_h - \beta_v - (\beta_h - \beta_v)\cos 2\theta + (\beta_h - \beta_v)\sin 2\theta / \mu\right]} \cdot$$
$$\left[\{(K+1) + (K-1)\cos 2\theta - (K-1)\sin 2\theta/\mu\}\sigma_{v0} - \{(\beta_h + \beta_v) + (\beta_h - \beta_v)\cos 2\theta - (\beta_h - \beta_v)\sin 2\theta/\mu\}P_{pi} - \frac{2\alpha_T E\Delta T}{1-2\nu}\right]$$

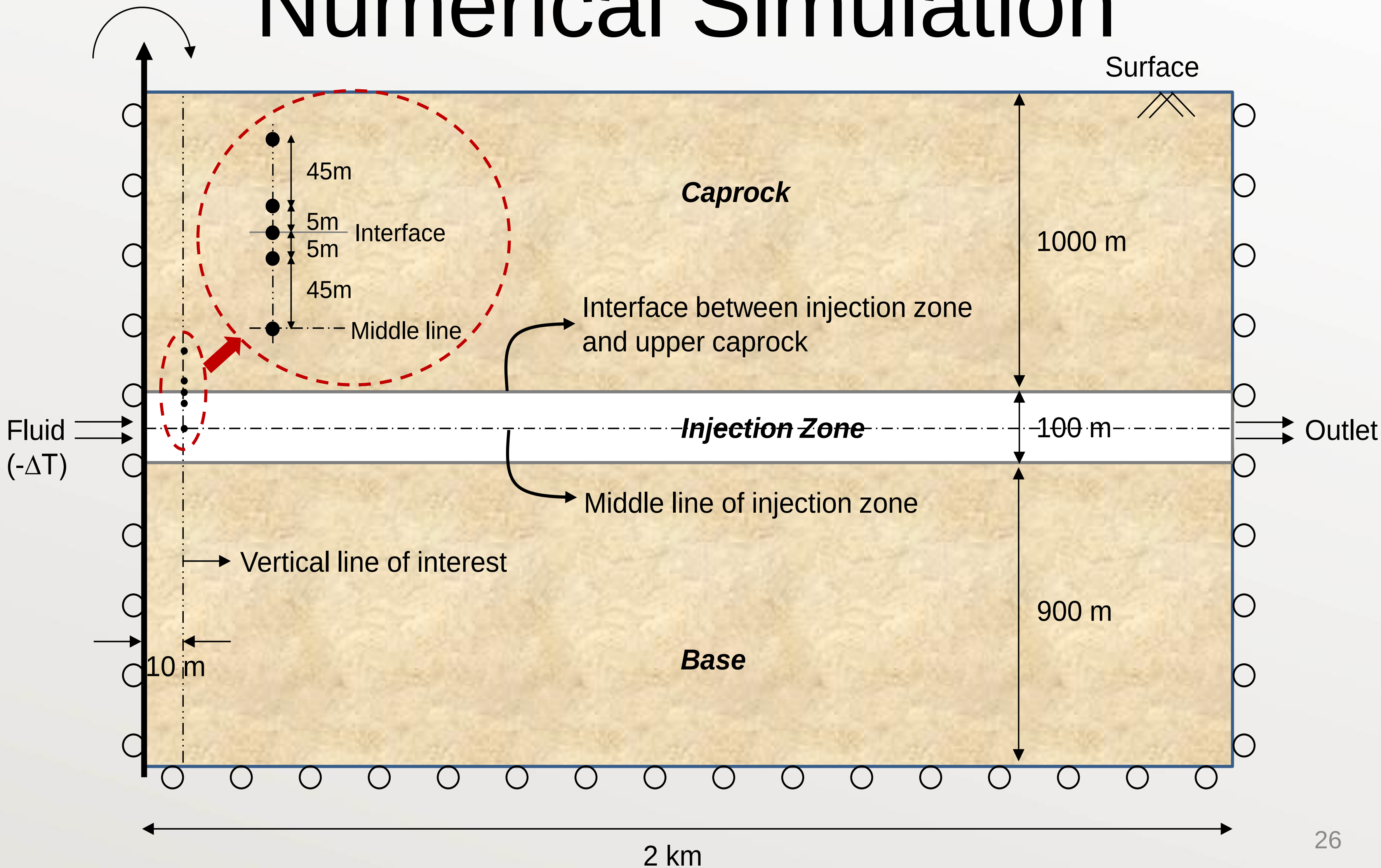
- Strike-slip fault system

$$P_{\max} = \frac{1}{\alpha - \beta_h}\left[\left(\frac{1+K_H}{2} + \frac{1-K_H}{2}\cos 2\theta - \frac{1-K_H}{2}\sin 2\theta/\mu\right)\sigma_{H0} - \beta_h \cdot P_{pi} - \frac{\alpha_T E\Delta T}{1-2\nu}\right]$$

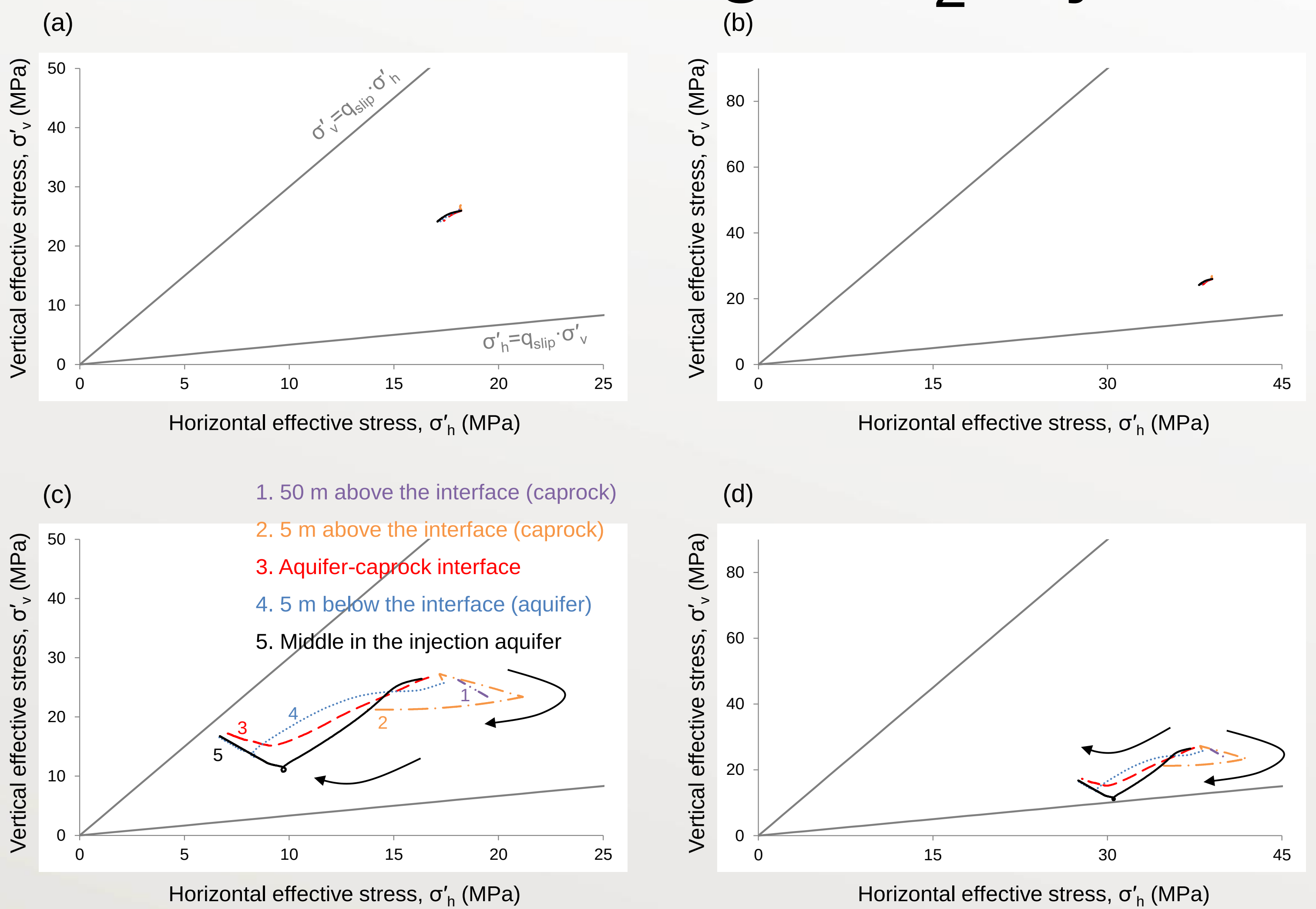
$$\Delta P_{max} = P_{max} - P_{pi}$$

- Kim, S, and Hosseini, S. A., 2014, Geological CO_2 storage: incorporation of pore-pressure/stress coupling and thermal effects to determine maximum sustainable pressure limit: Energy Procedia, v. 63, p. 3339-3346,
- Kim, S, and Hosseini, S. A., 2016, Study on the Ratio of Pore-Pressure/Stress Changes During Fluid Injection and Its Implications for CO2 Geologic Storage, Journal of Petroleum Science and Engineering, in press.

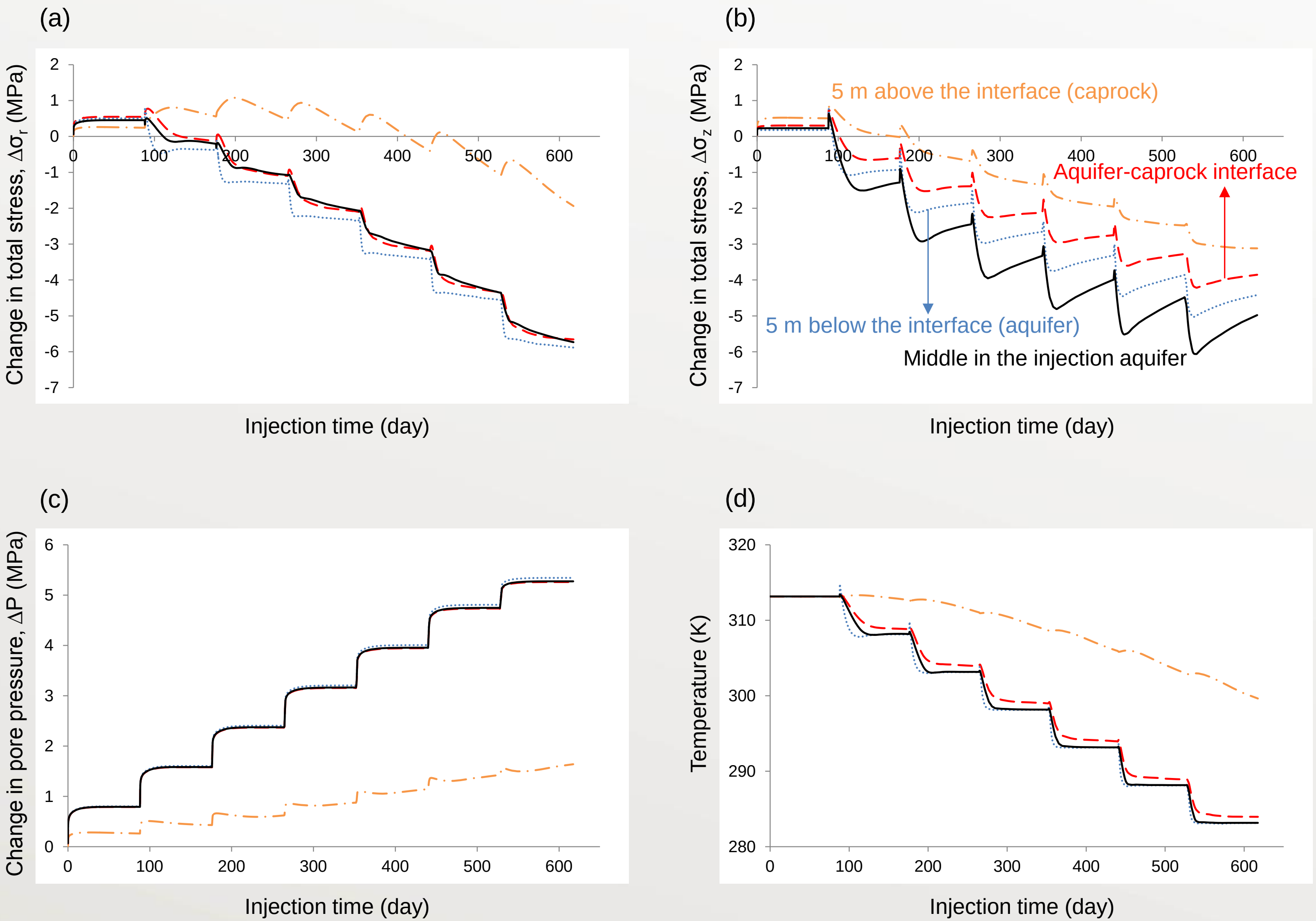
Numerical Simulation



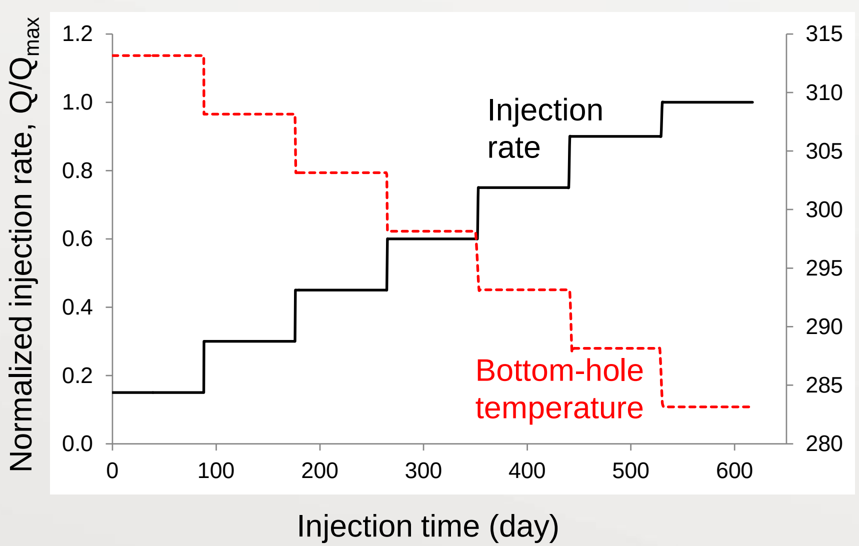
Stress Path During CO_2 Injection

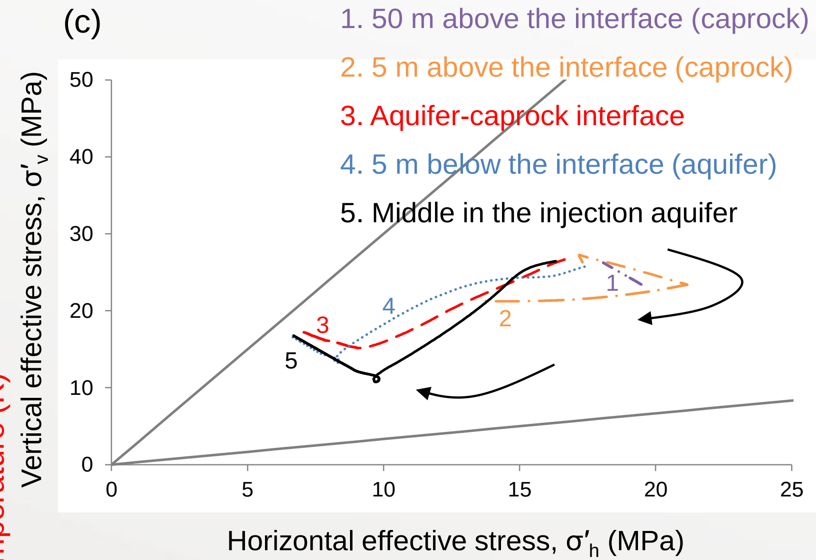


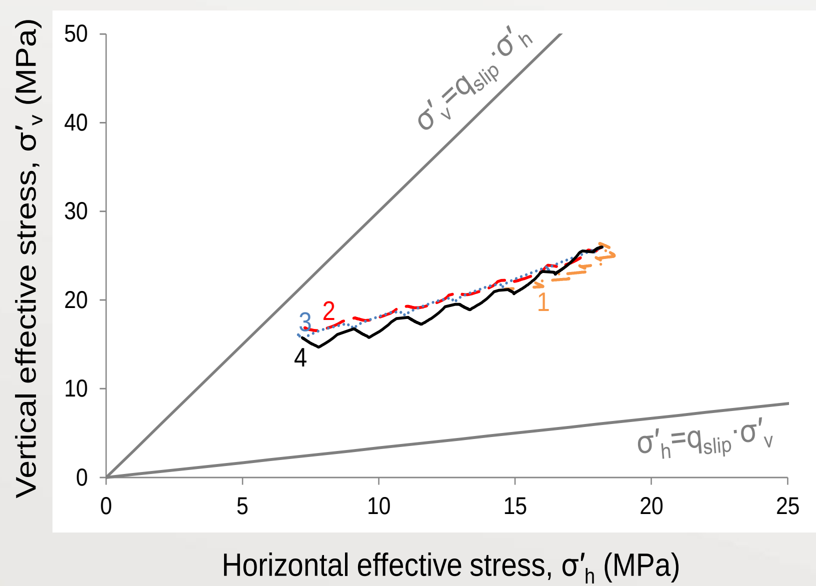
Stepwise Injection



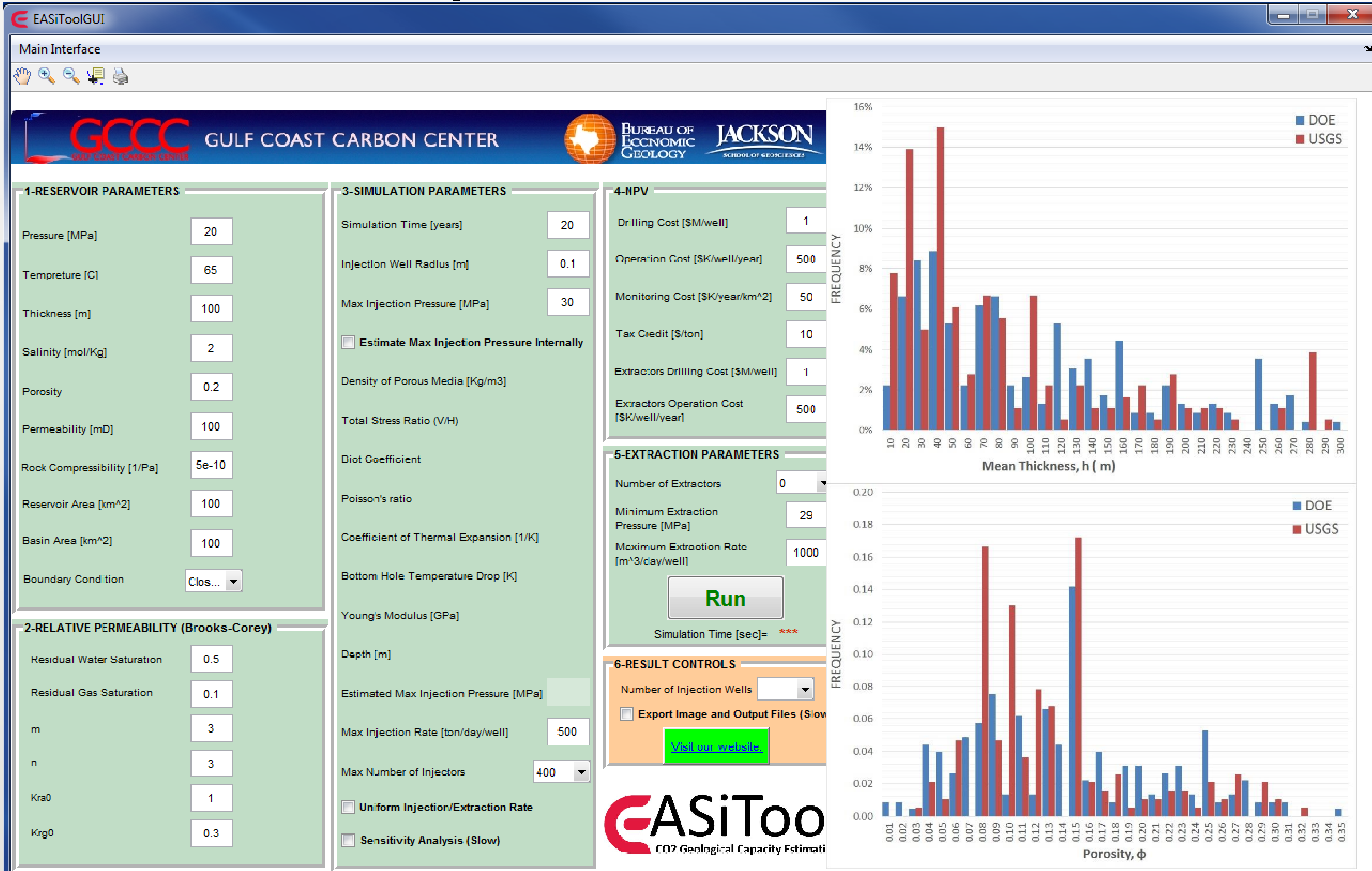
Stress Path During CO_2 Injection



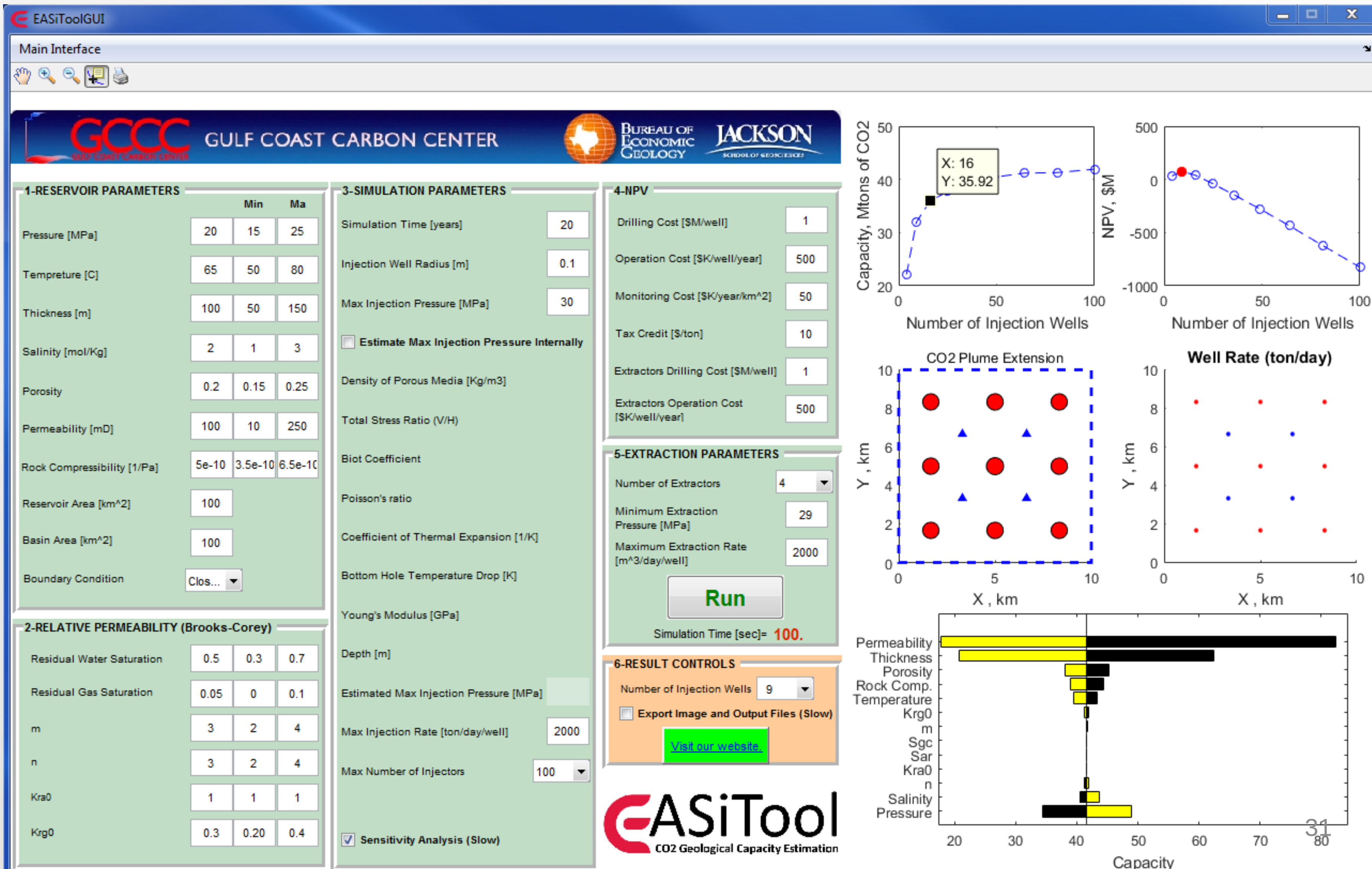




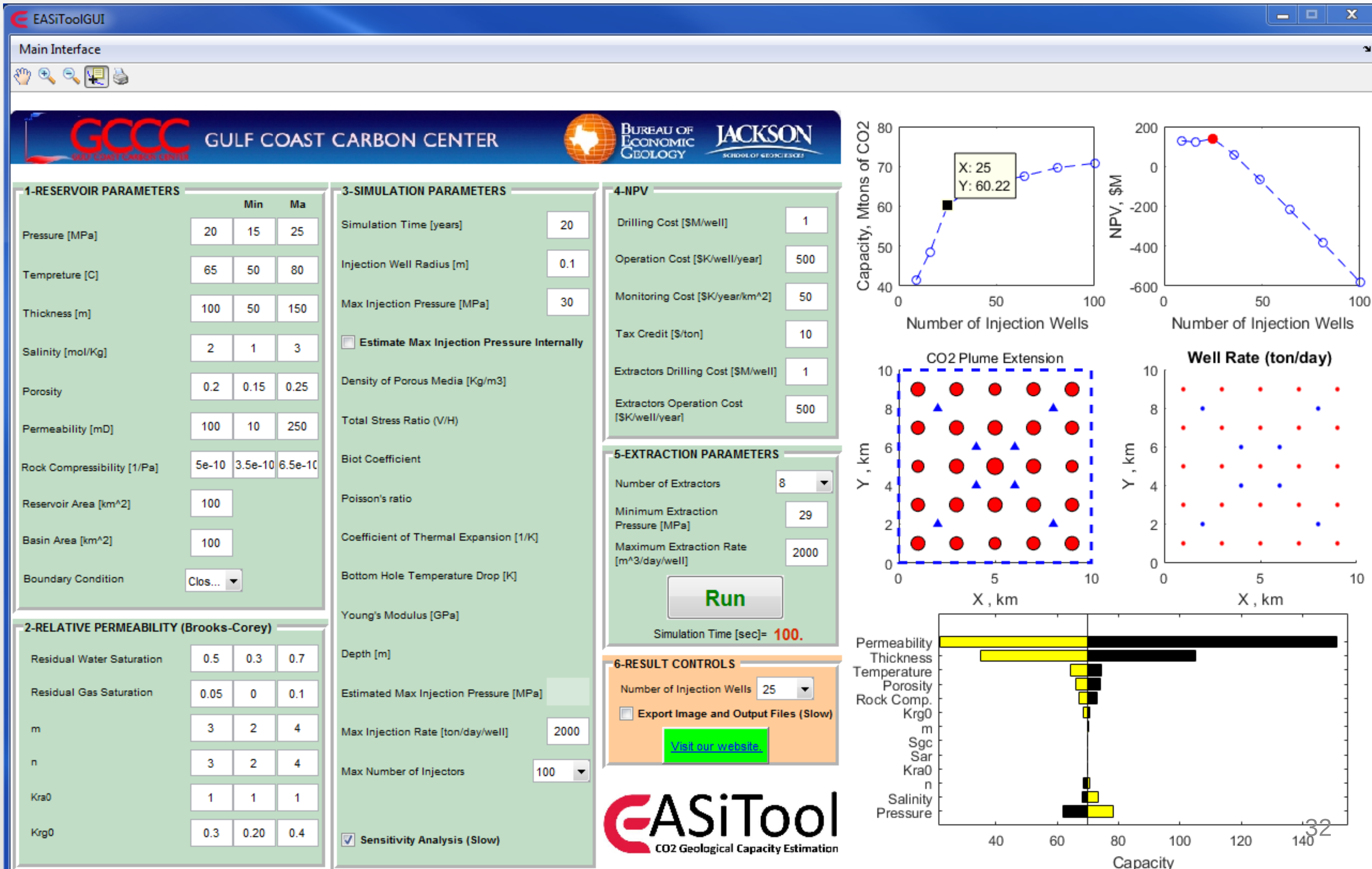
Input Parameters



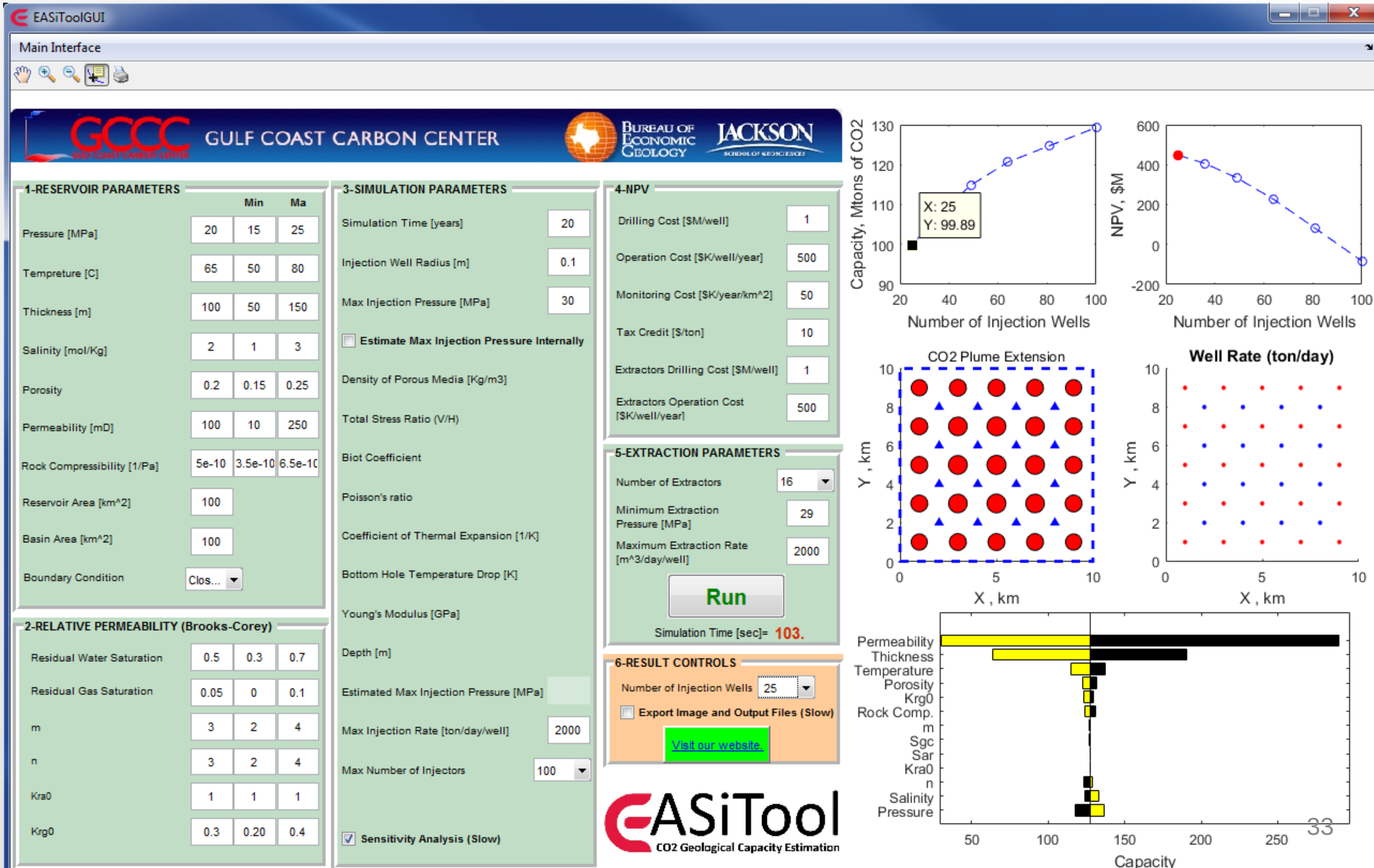
Closed Boundary, 4 Extractors



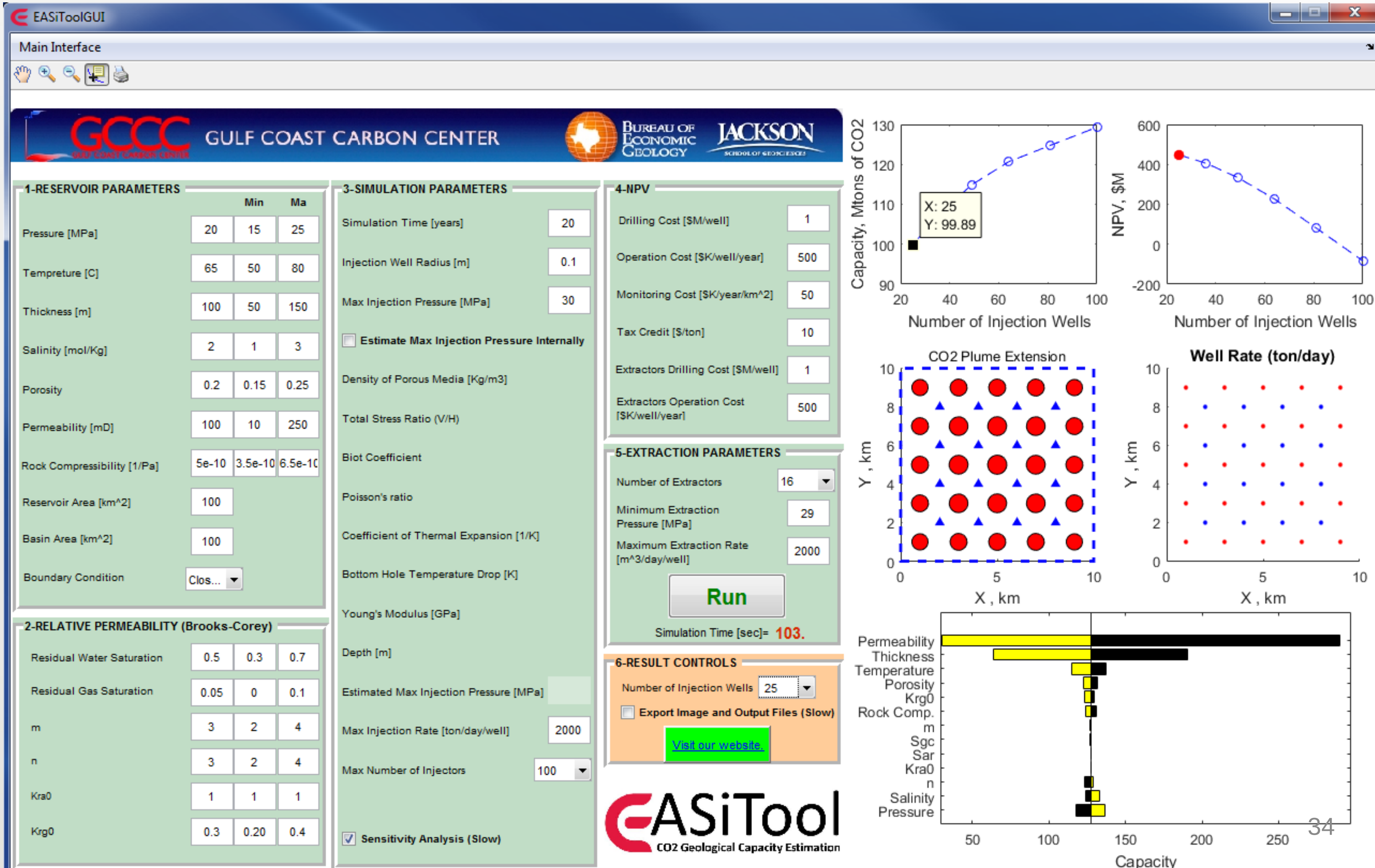
Closed Boundary, 8 Extractors



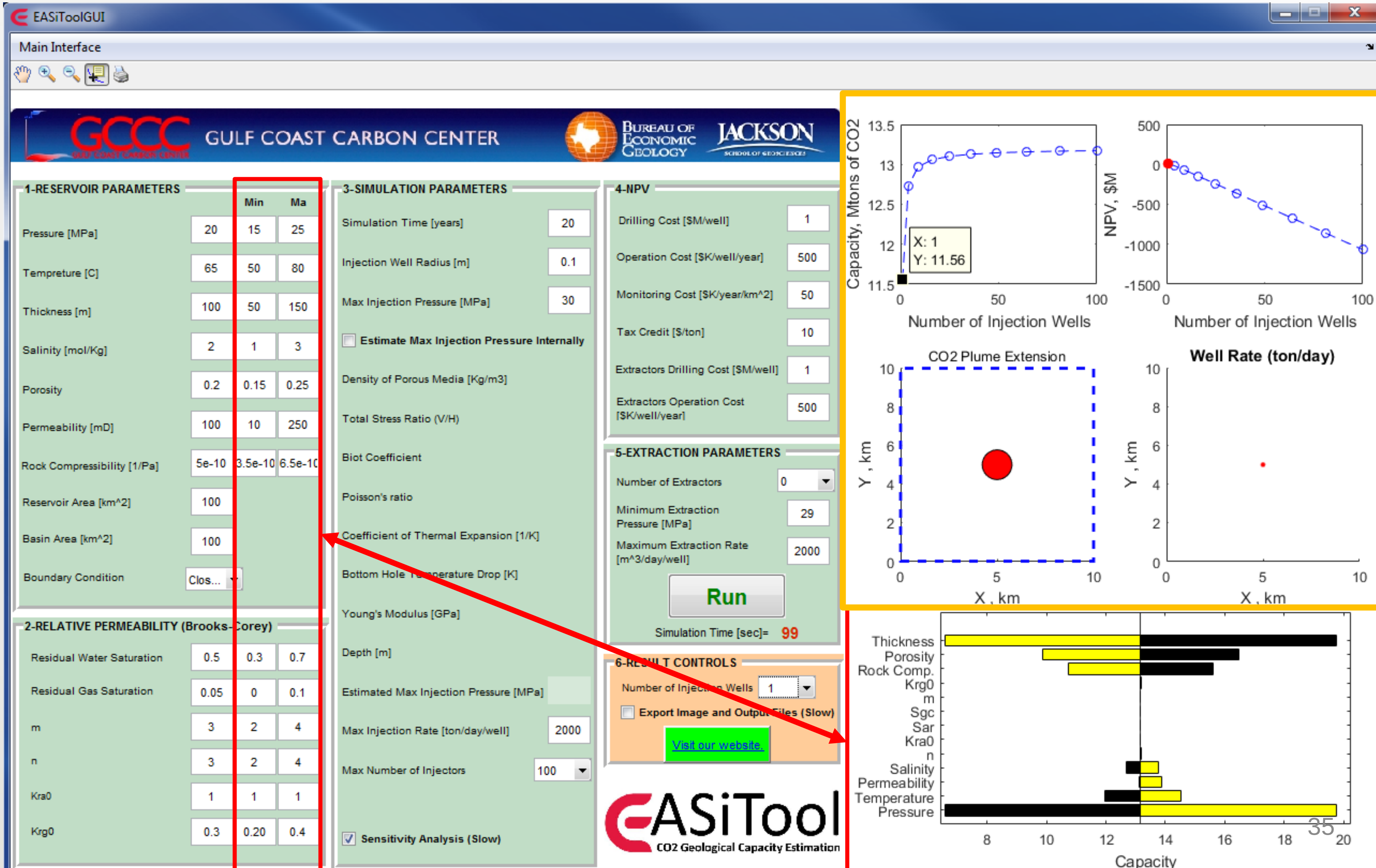
Closed Boundary, 16 Extractors



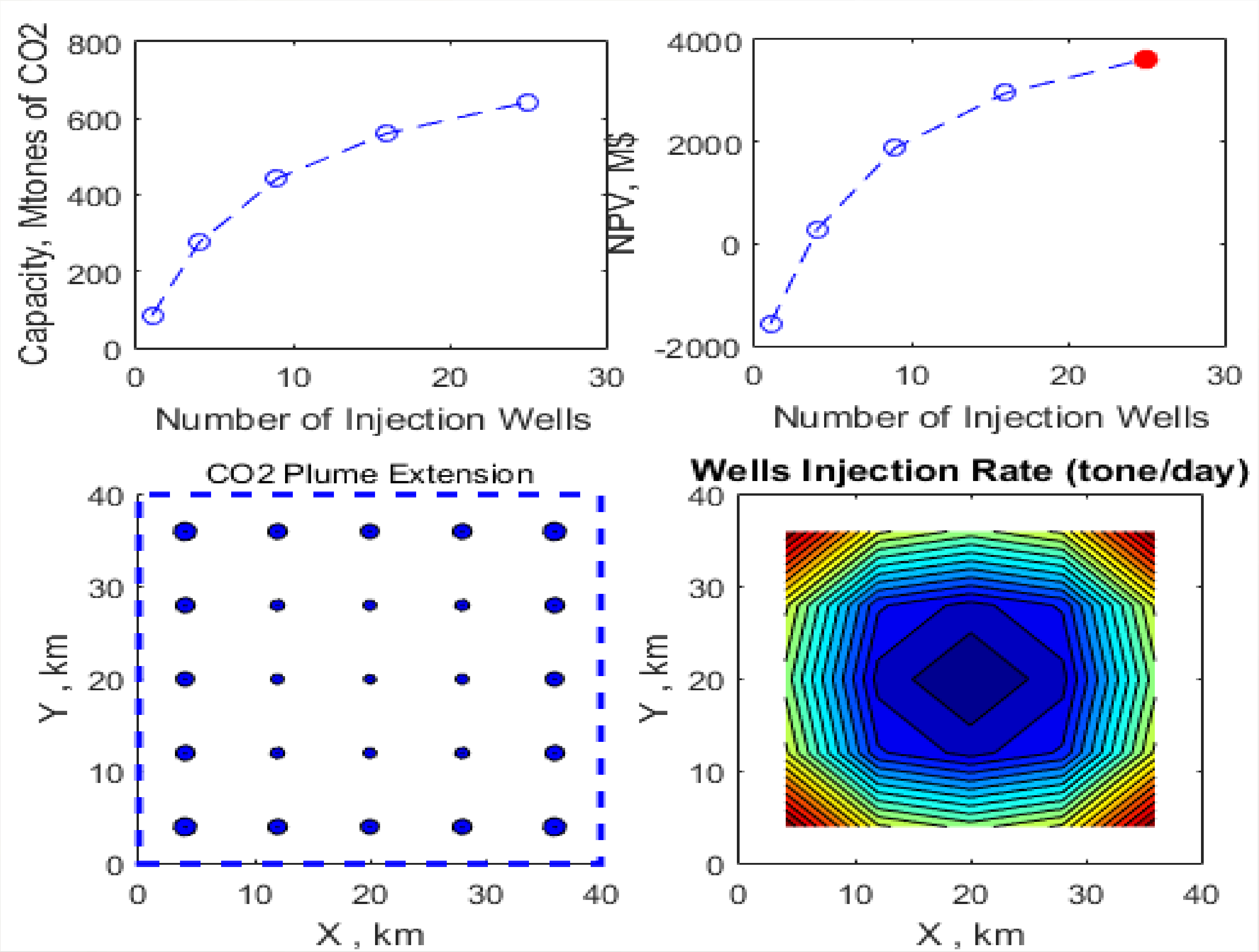
Closed Boundary, 16 Extractors



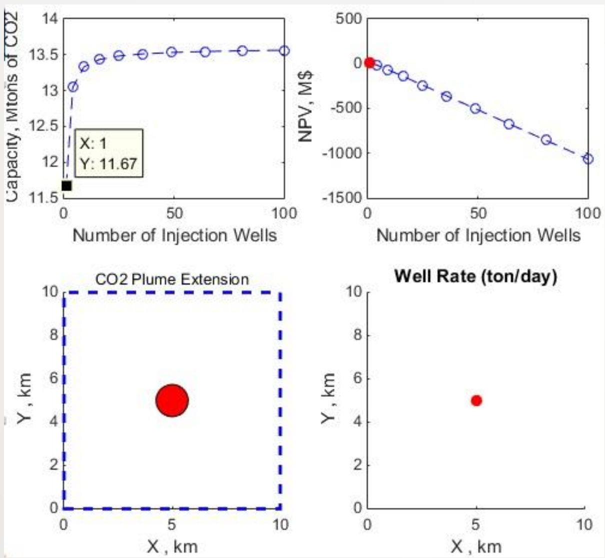
Sensitivity Analysis



EASiTool – Interface 7



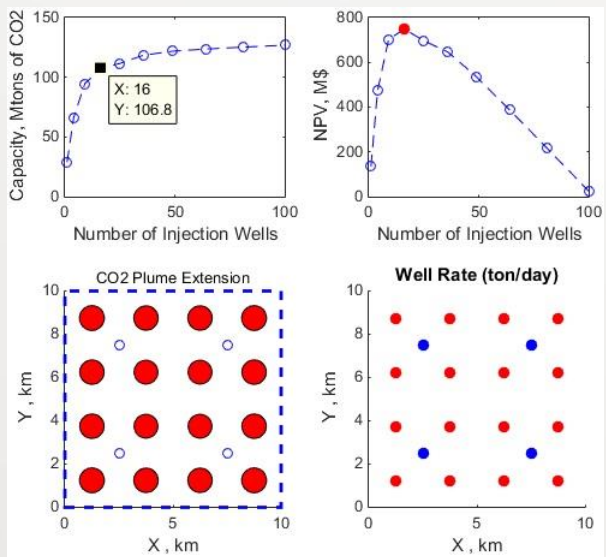
Extraction Results



0 Extractors

Capacity: 11.7 Mton

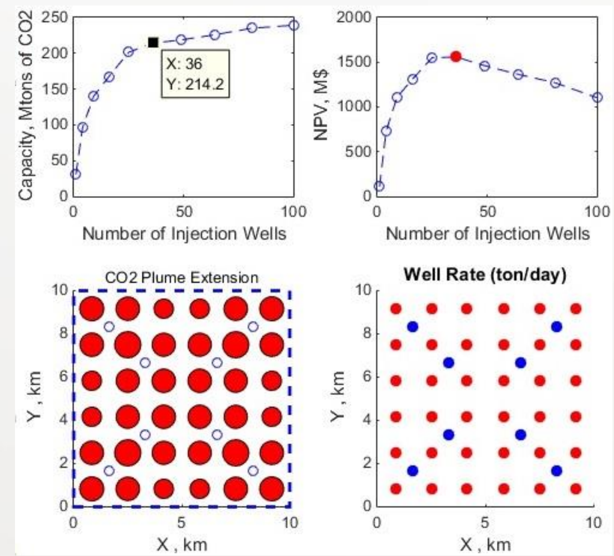
1 injector



4 Extractors

Capacity 107 Mton

16 injectors

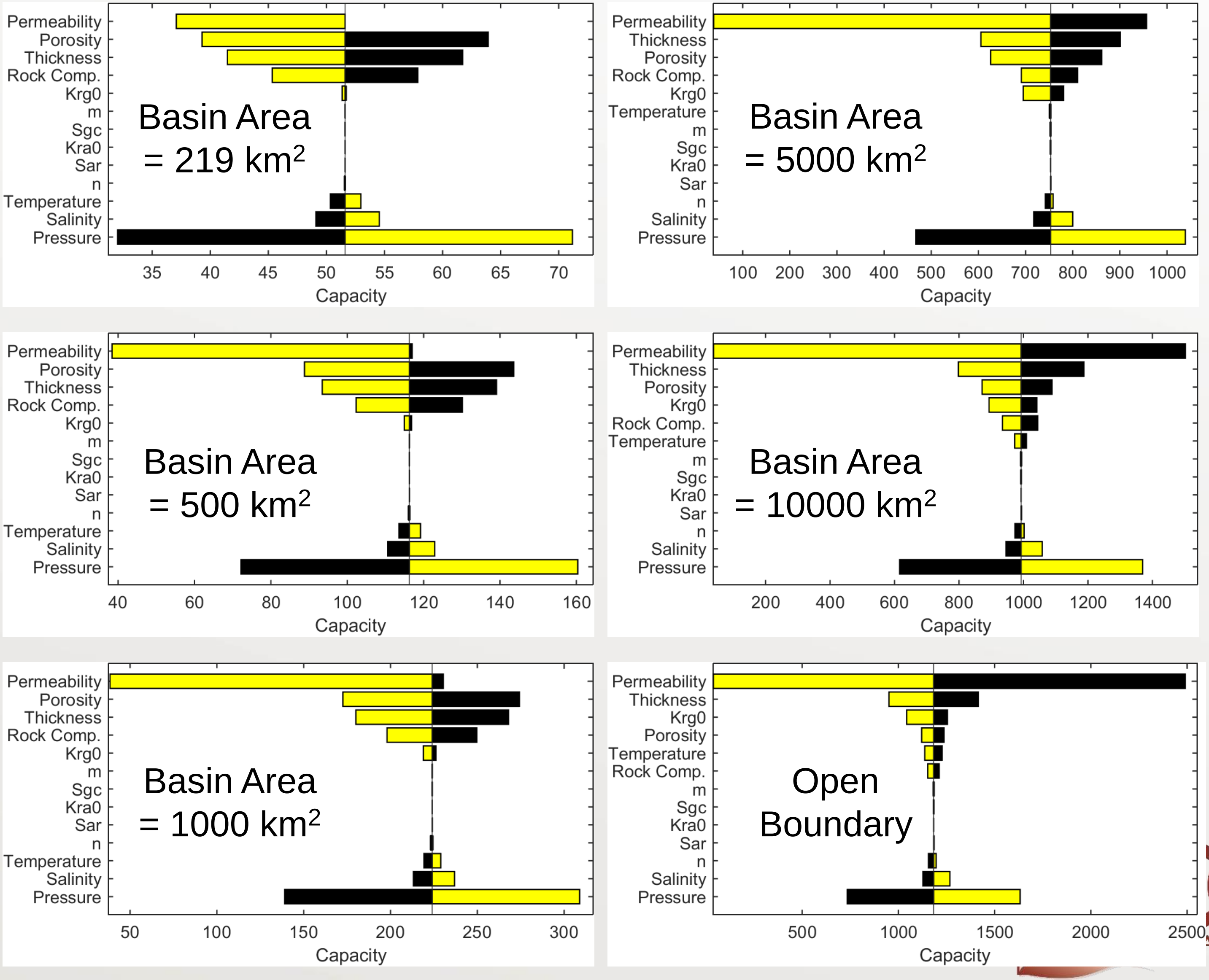


8 Extractors

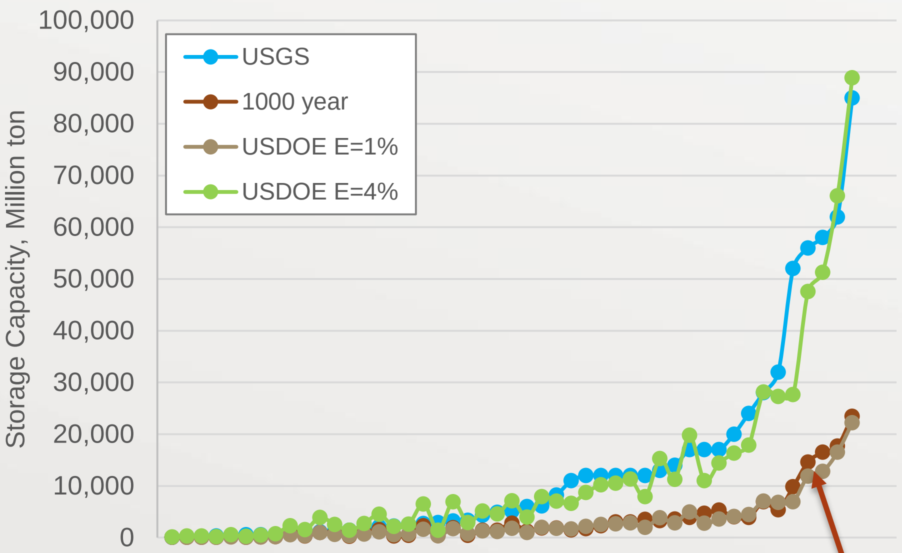
Capacity: 214 Mton

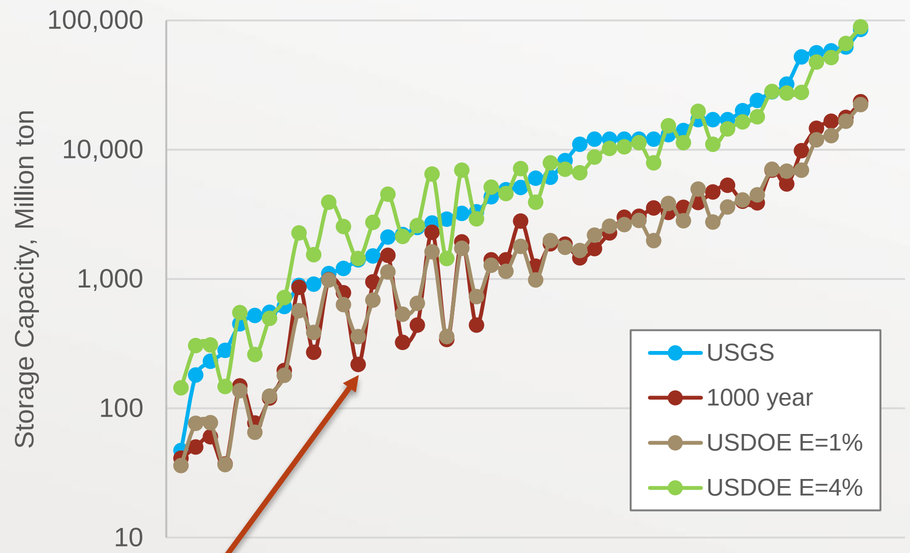
36 injectors

Reservoir Area = 219 km^2



EASiTool vs Static Methods





EASiTool 1000 years

EASiTool 4.0

Injection time, year	2
Basin size, km^2	20 km × 10 km
Number of injectors	114
Number of extractors	12
Injection rate, ton/day	100 – 500
Extraction rate, m^3/day	200

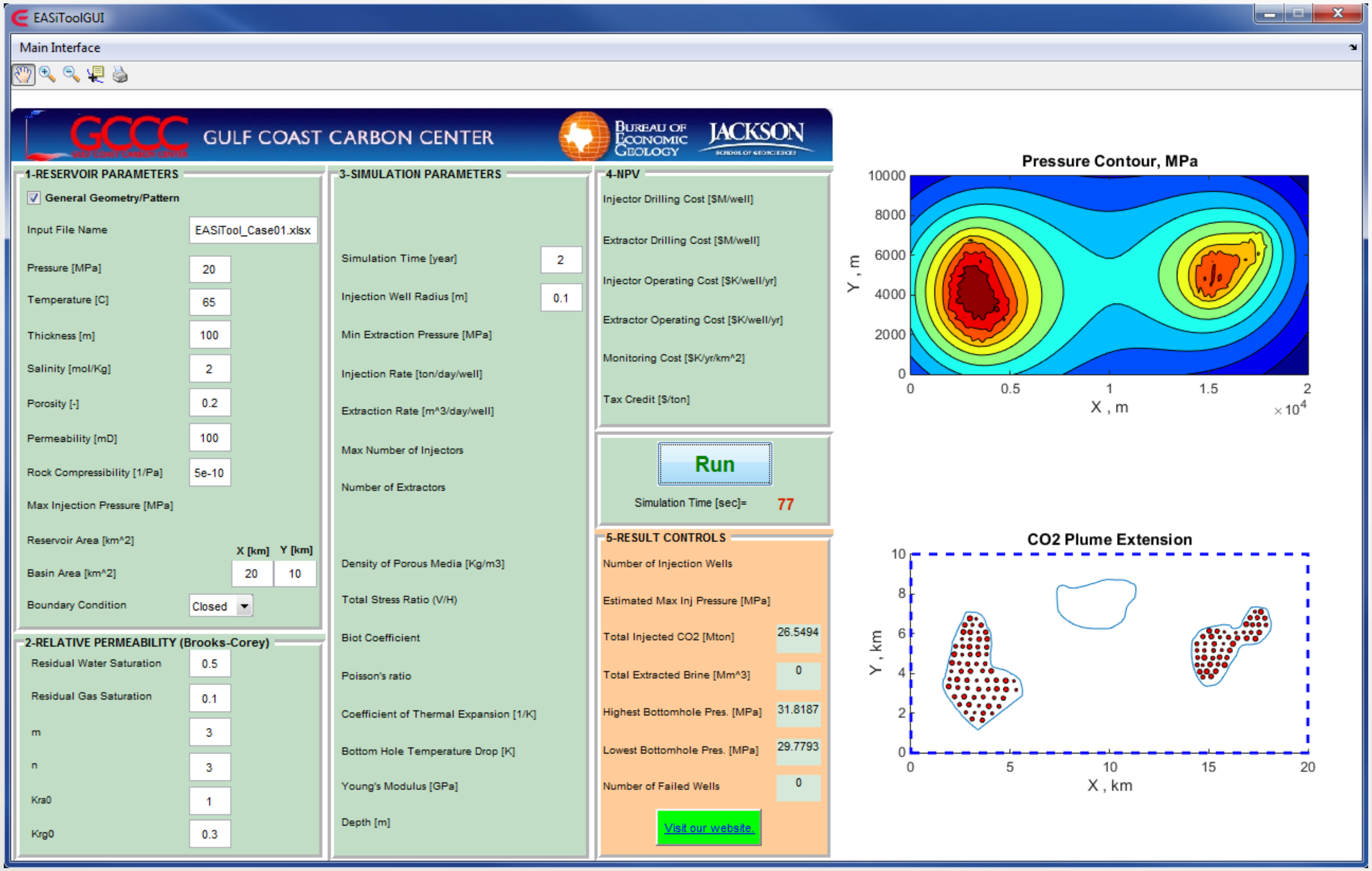
EASiTool 4.0

Well Number	Well X (m)	Well Y (m)	Injection Rate (Ton/day)	Extraction Rate (m^3/day)	Max Injection Pressure (Mpa)	Min Extraction Pressure (Mpa)	Well Type (0 for Injector/1 for Extractor)
1	2973.80	6768.29	500	0	35	20	0
2	3290.68	6743.90	134	0	35	20	0
3	2717.85	6439.02	378	0	35	20	0
4	3095.67	6439.02	174	0	35	20	0
5	3534.43	6426.83	367	0	35	20	0
6	2644.73	6085.37	446	0	35	20	0
7	2985.98	6073.17	429	0	35	20	0
8	3375.99	6073.17	138	0	35	20	0
9	3766.00	6073.17	405	0	35	20	0
10	3839.12	5731.71	432	0	35	20	0
11	3436.93	5719.51	421	0	35	20	0
12	2985.98	5719.51	159	0	35	20	0
13	2571.60	5731.71	157	0	35	20	0
14	2254.72	5365.85	276	0	35	20	0
15	2608.17	5353.66	274	0	35	20	0
//							
115	3193.17	5865.85	0	200	35	20	1
116	3120.05	4719.51	0	200	35	20	1
117	3436.93	3902.44	0	200	35	20	1
118	2595.98	3487.80	0	200	35	20	1
119	4095.06	3451.22	0	200	35	20	1
120	3839.12	2597.56	0	200	35	20	1
121	2864.11	2658.54	0	200	35	20	1
122	17343.08	6243.90	0	200	35	20	1
123	14990.86	5670.73	0	200	35	20	1
124	15917.12	5317.07	0	200	35	20	1
125	15003.05	4975.61	0	200	35	20	1
126	15173.67	4256.10	0	200	35	20	1

Injectors

Extractors

EASiTool 4.0

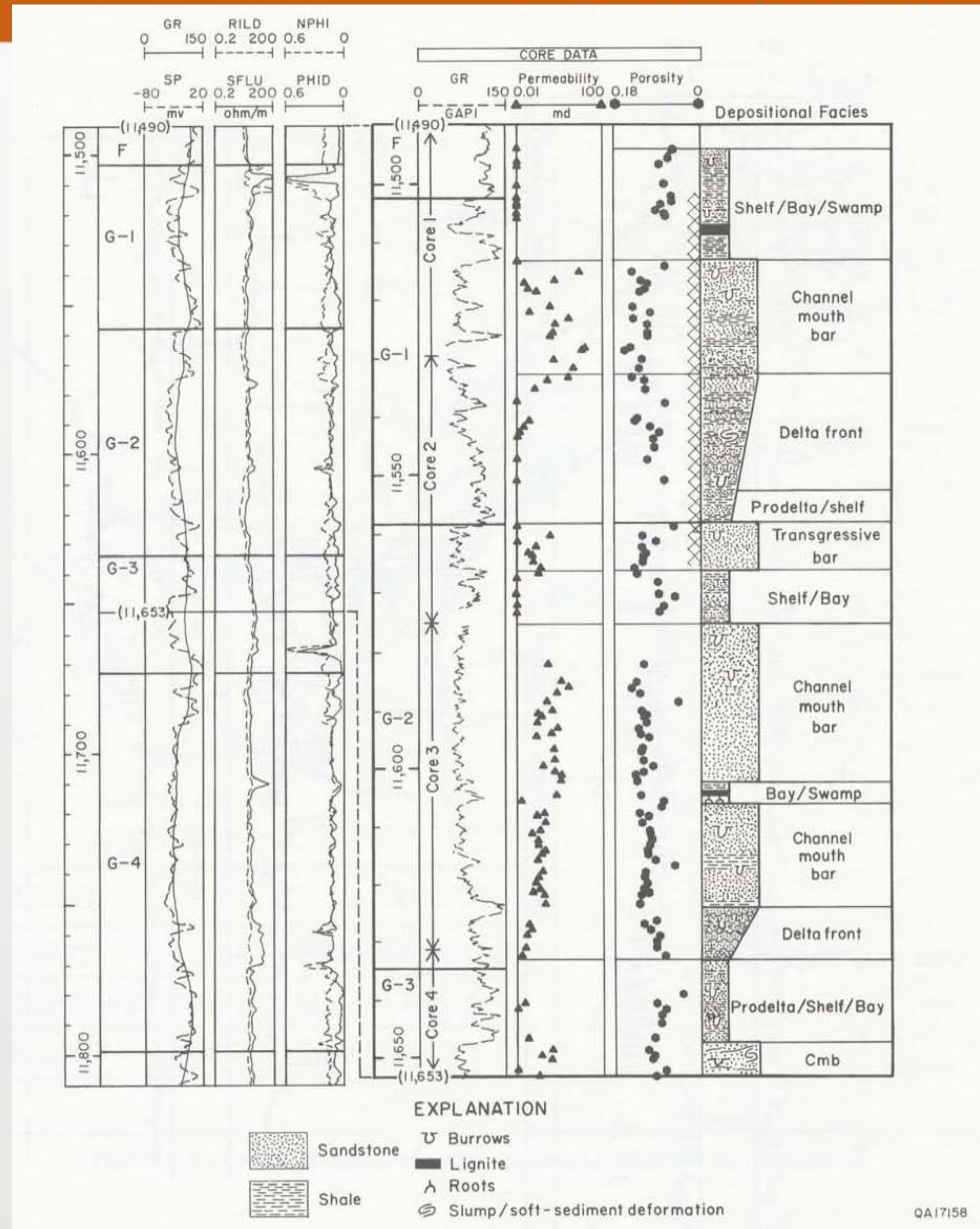

EASiToolGUI
Main Interface
GCCC GULF COAST CARBON CENTER
BUREAU OF ECONOMIC GEOLOGY
JACKSON SCHOOL OF GEOSCIENCES
1-RESERVOIR PARAMETERS
General Geometry/Pattern
Input File Name EASiTool_Case01.xlsx
Pressure [MPa] 20
Temperature [C] 65
Thickness [m] 100
Salinity [mol/Kg] 2
Porosity [-] 0.2
Permeability [mD] 100
Rock Compressibility [1/Pa] 5e-10
Max Injection Pressure [MPa]
Reservoir Area [km^2]
X [km] Y [km]
Basin Area [km^2] 20 10
Boundary Condition Closed
2-RELATIVE PERMEABILITY (Brooks-Corey)
Residual Water Saturation 0.5
Residual Gas Saturation 0.1
m 3
n 3
Kra0 1
Krg0 0.3
3-SIMULATION PARAMETERS
Simulation Time [year] 2
Injection Well Radius [m] 0.1
Min Extraction Pressure [MPa]
Injection Rate [ton/day/well]
Extraction Rate [m^3/day/well]
Max Number of Injectors
Number of Extractors
Density of Porous Media [Kg/m3]
Total Stress Ratio (V/H)
Biot Coefficient
Poisson's ratio
Coefficient of Thermal Expansion [1/K]
Bottom Hole Temperature Drop [K]
Young's Modulus [GPa]
Depth [m]
4-NPV
Injector Drilling Cost [$M/well]
Extractor Drilling Cost [$M/well]
Injector Operating Cost [$K/well/yr]
Extractor Operating Cost [$K/well/yr]
Monitoring Cost [$K/yr/km^2]
Tax Credit [$/ton]
Run
Simulation Time [sec]= 77
5-RESULT CONTROLS
Number of Injection Wells
Estimated Max Inj Pressure [MPa]
Total Injected CO2 [Mton] 26.5494
Total Extracted Brine [Mm^3] 0
Highest Bottomhole Pres. [MPa] 31.8187
Lowest Bottomhole Pres. [MPa] 29.7793
Number of Failed Wells 0
Visit our website.
Pressure Contour, MPa
Y , m
X , m
×10^4
CO2 Plume Extension
Y , km
X , km

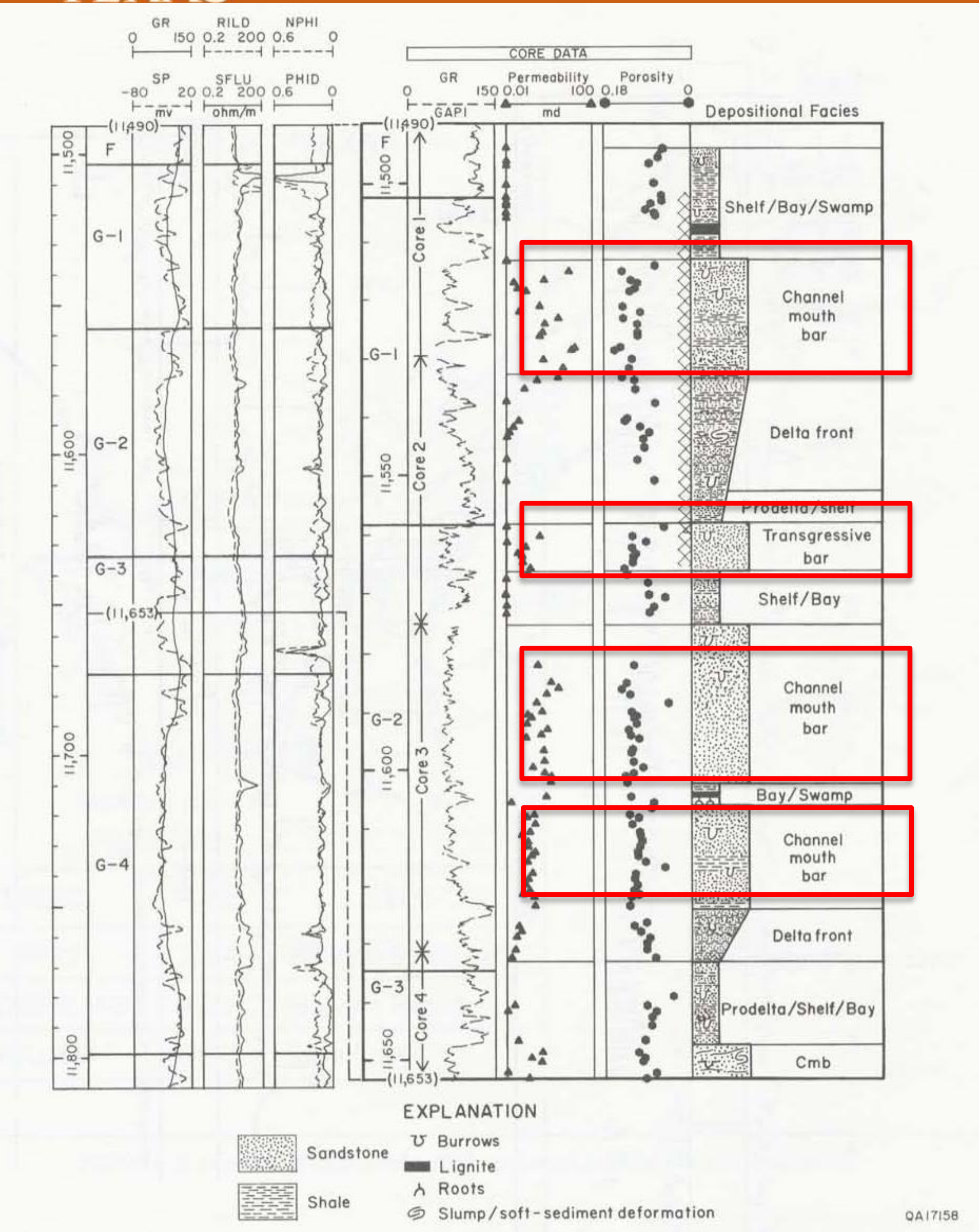
END PART I

Exercise

- A) $$\boxed{\frac{1641\times10^{6}\,J}{s}\times\frac{365\times24\times3600s}{year}=5.17\times10^{16}\,J/yr}$$
- B) $$\boxed{\frac{7100BTU}{lb}\times\frac{1lb}{.454kg}\times\frac{1055J}{BTU}\times\frac{1000kg}{ton}=1.65x10^{10}\,\frac{J}{ton\ coal}}$$
- C) $$\boxed{\frac{5.17\times10^{16}\,J}{yr}\times\frac{ton\ coal}{1.65\times10^{10}\,J}\times\frac{1}{.5}=6.3\times10^{6}\,\frac{\text{ton coal}}{year}}$$
- D) $$\boxed{\frac{6.3\times10^{6}\ \text{ton coal}}{yr}\times\frac{2ton\ CO_2}{\text{ton coal}}=12.6\times10^{6}\,\frac{ton\ CO_2}{year}}$$
- E) $$\boxed{\frac{12.6\times10^{6}\ \text{ton}}{yr}\times\frac{18.95Mscf}{ton}\times\frac{1MMscf}{1000Mscf}\times\frac{1year}{365days}=651MMscfd}$$
- F) **378 million tonnes over 30 years**

Storage Target: Wilcox Formation, Fluvial Sandstone





Formation

Table 1: Template input

Initial pressure, MPa	**21.7**
Initial temperature, °C	**69**
Thickness, m	**200 (10XWilcox)**
Salinity, kg/mol	**2**
Porosity	**0.15**
Permeability, mD	**10**
Rock compressibility, 1/Pa	**5.0E-11**
Reservoir area, km^2	**1600**
Basin area, km^2	**1600**
Boundary Condition	**Closed or Open**

Table 2: Relative permeability parameters for Brooks-Corey model

Residual water saturation, S_{wr}	**0.2**
Residual gas saturation, S_{gr}	**0.1**
Water exponent, m	**3.0**
Gas exponent, n	**3.0**
Water end point relative permeability, k°_{rw}	**1.0**
Gas end point relative permeability, k°_{rg}	**0.8**

Table 3: Simulation parameters

Simulation time, year	**30**
Injection well radius, m	**1**
Maximum injection pressure, MPa	**43.4**

EASiTool – Wilcox Formation

1. How many wells are required to store 378 million tone of CO_2 for open boundary condition? What is the optimum number of injection wells?

2. How many wells are required to store 378 million tonne of CO_2 for closed boundary condition? What is the optimum number of injection wells?

3. Double the basin area for closed boundary condition and redo question 2. Explain the change.

Table 1: Template input

Initial pressure, MPa	21.7
Initial temperature, °C	69
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Salinity, kg/mol	2
Porosity	0.15
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Rock compressibility, 1/Pa	5.0E-11
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Basin area, km^2	1600
Boundary Condition	Closed or Open

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Table 3: Simulation parameters

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Maximum injection pressure, MPa	43.4

Wilcox

1. How many wells are required to store 378 million tone of CO_2 for open boundary condition? What is the optimum number of injection wells?
    1. 9 wells, NPV: 64 wells and 9<64 is good.
    2. Extra: 428.3 million tone; Max injection rate: 4897 tonne/day; optimum 4263 M$
2. How many wells are required to store 378 million tonne of CO_2 for closed boundary condition? What is the optimum number of injection wells?
    1. 64 wells, NPV: 25 and 64>25 is not good.
    2. Extra: 381 million tone; Max injection rate: 1374 tonne/day; optimum 625.6 M$
3. Double the basin area for closed boundary condition and redo question 2. Explain the change.
    1. 16 wells, NPV: 49 wells and 16<49 is good.
    2. Extra: 453.8 million tone; Max injection rate: 3456 tonne/day; optimum 2586 M$

Time lapse compressibility monitoring

- Monitors fluid compressibility changes with time in AZMI
- Given the large compressibility difference between brine and CO_2, any considerable CO_2 leakage into a formation originally filled with brine is expected to increase overall compressibility of the formation.
- If this leakage happens to be near the monitoring wells running interference tests, appropriate interpretations can help in an understanding of the system's behavior.
- This technique requires a brine-saturated monitoring formation with near-zero gas saturation. It also requires a baseline test prior to CO_2 injection.

Time lapse compressibility monitoring

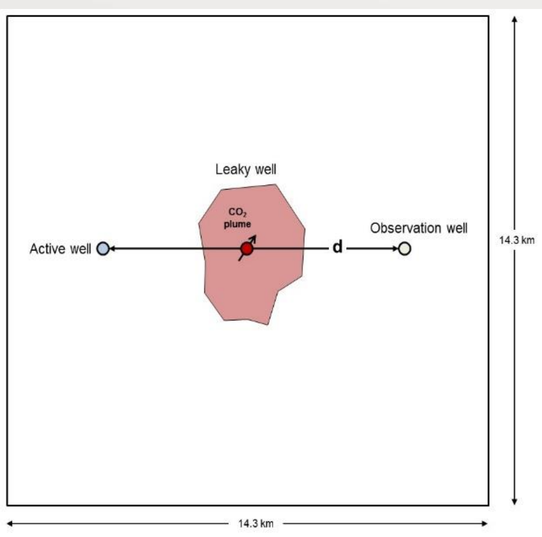
Above-zone; Active

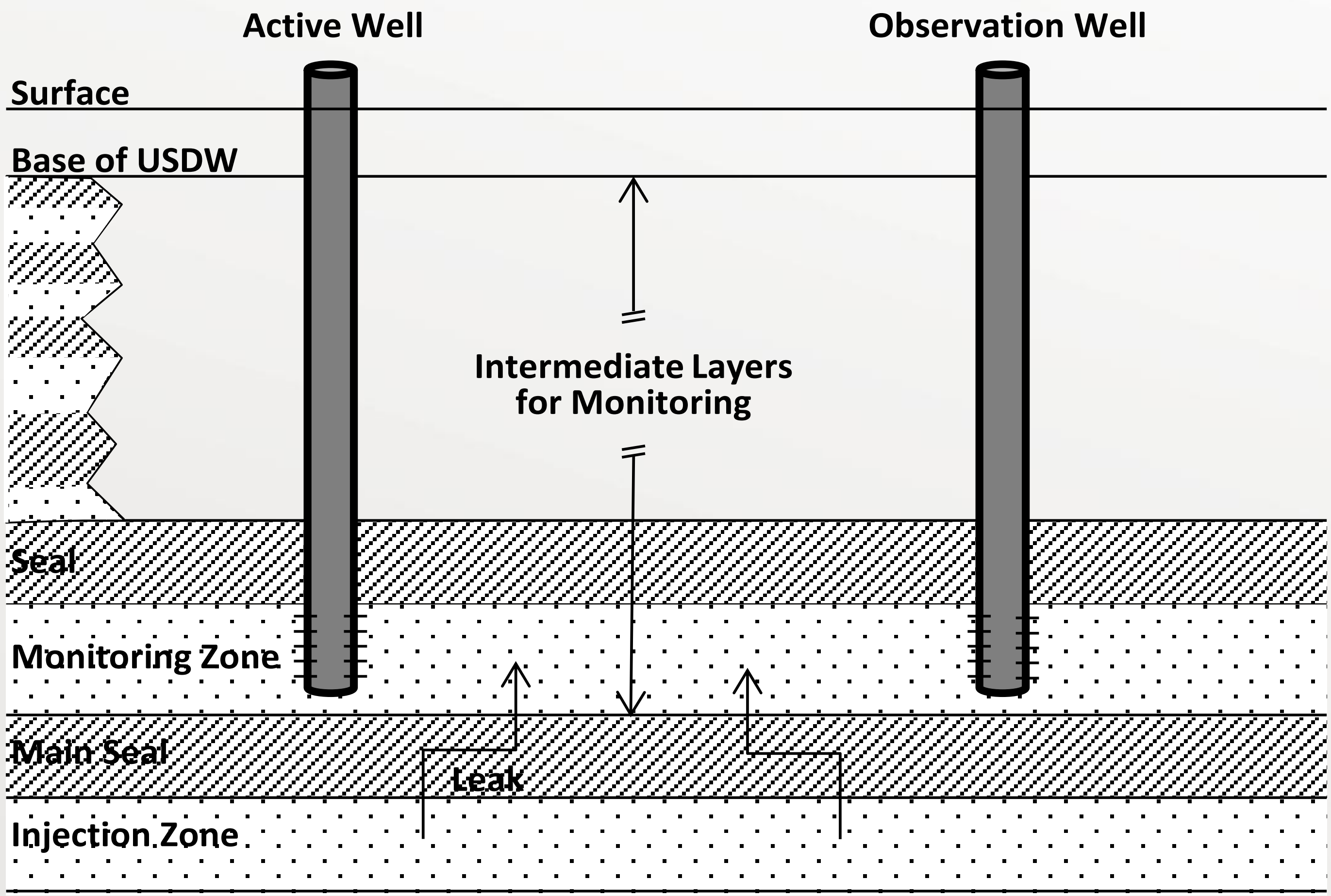
Storativity (S)= $\phi h c_t$

Transmissibility (T)=kh/μ

Diffusivity (D)=T/S

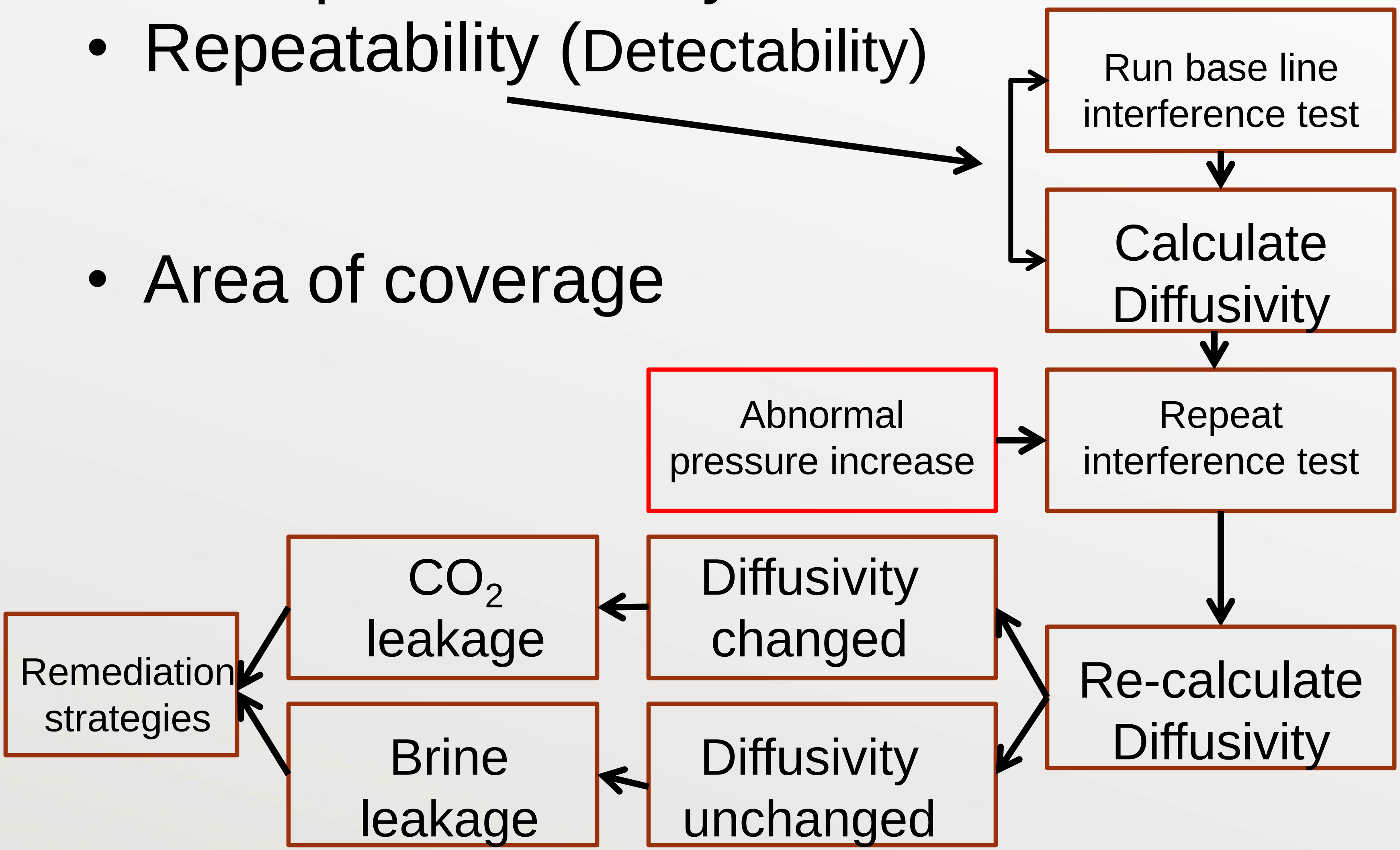
Map view of monitoring zone





Time-lapse Diffusivity

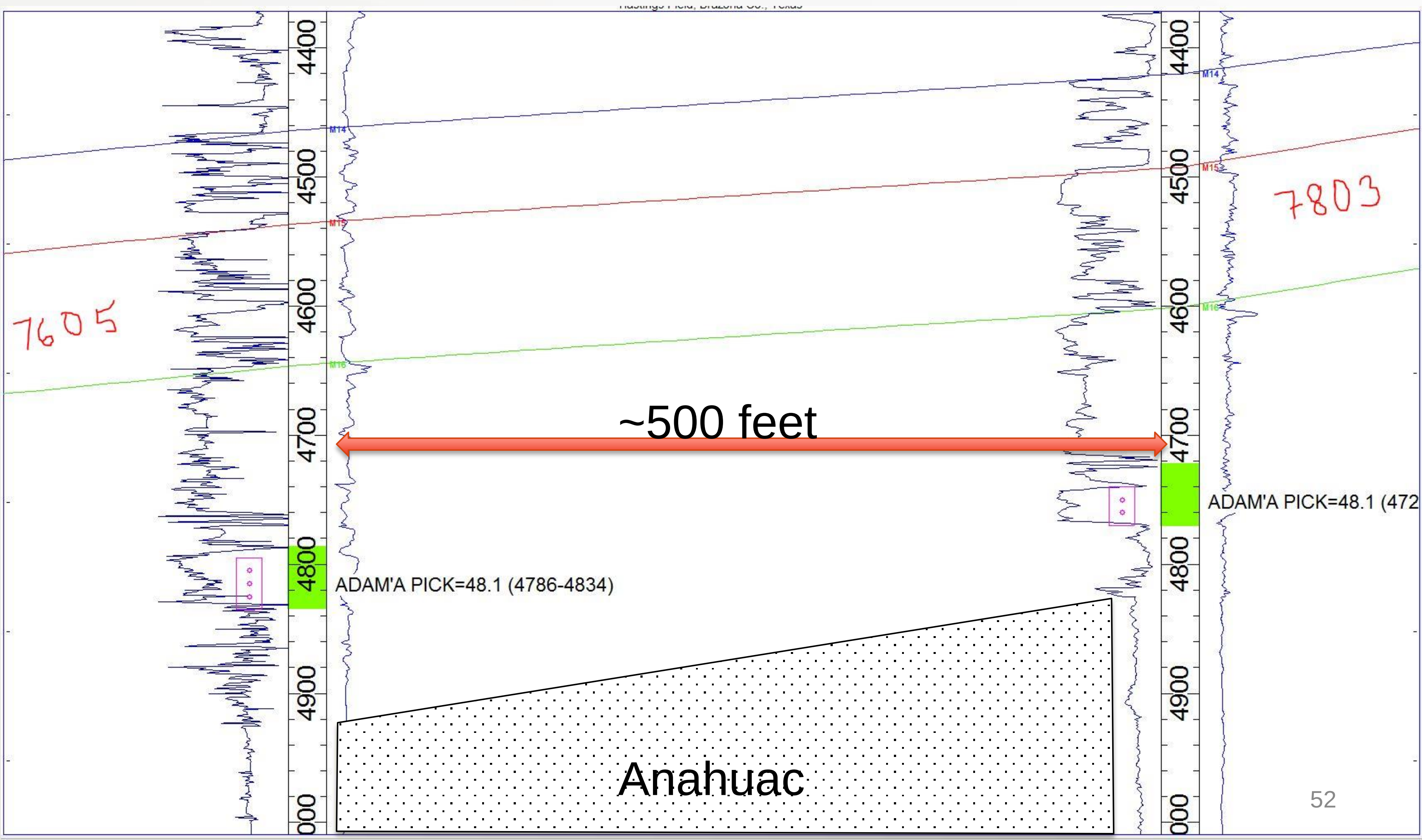
- Repeatability (Detectability)
- Area of coverage



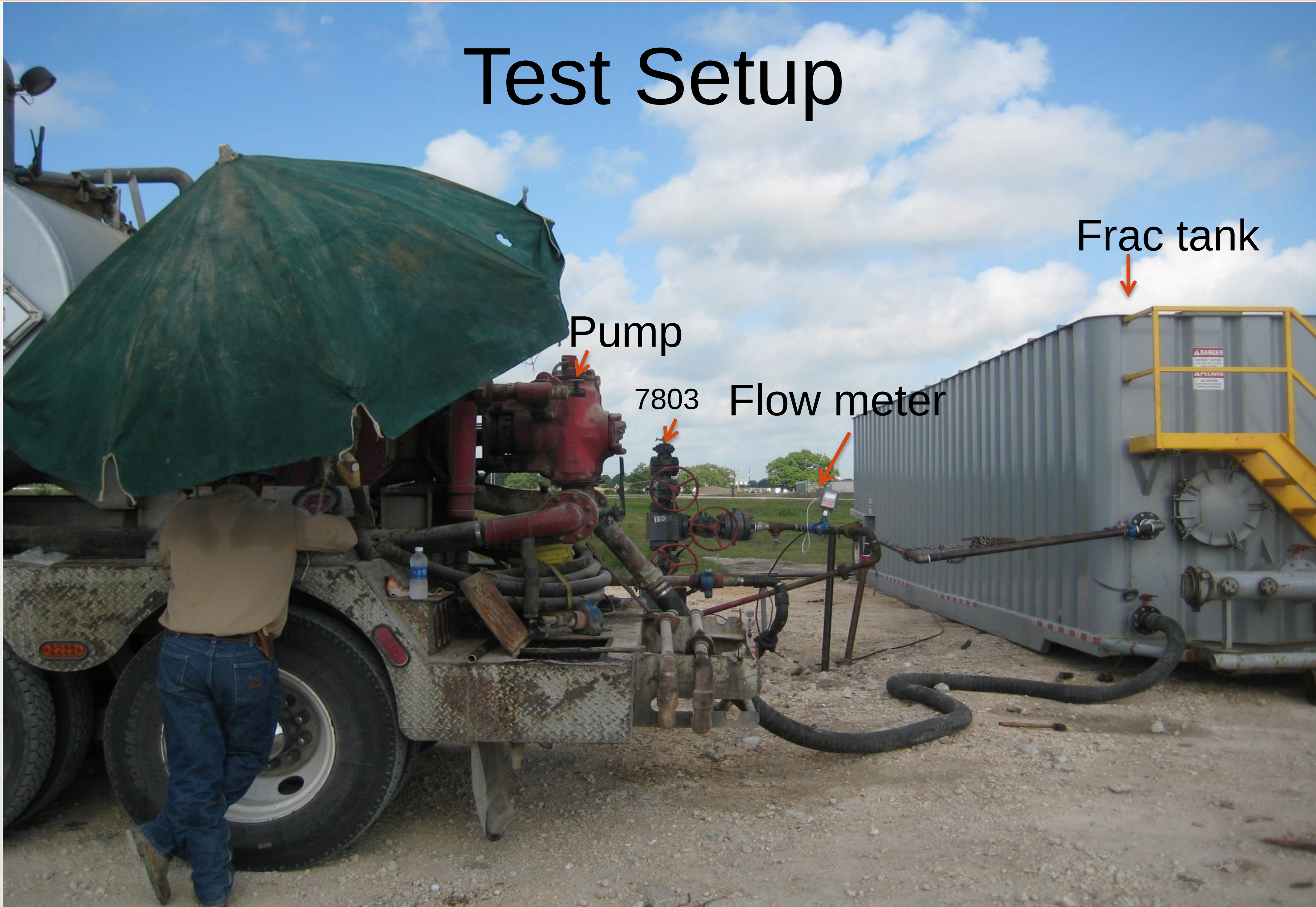
THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

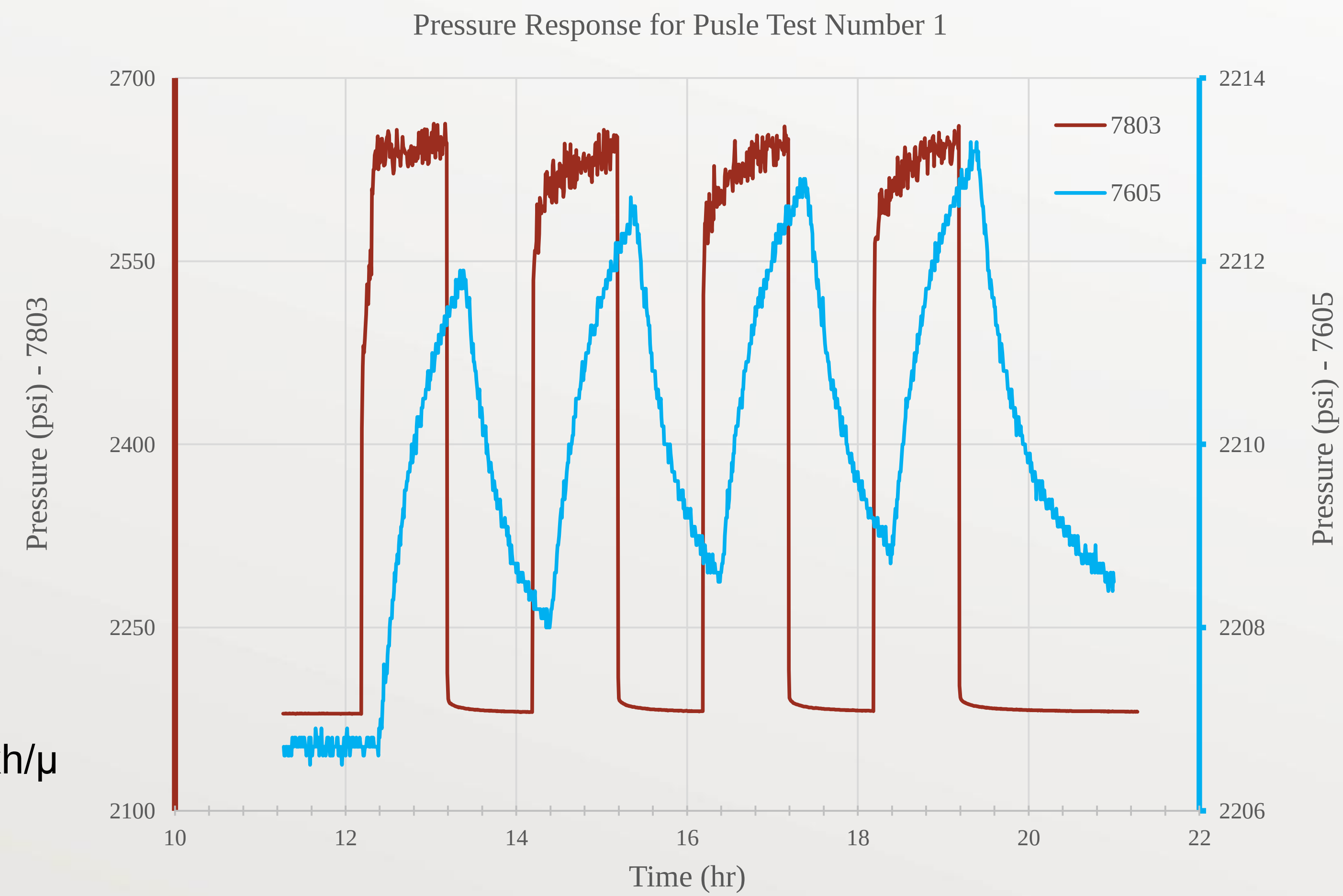
7803-7605 wells completed in M16 sand



Test Setup



Above-zone; Active



Storativity (S)= $\phi h c_t$

Transmissibility (T)=kh/μ

Diffusivity (D)=T/S

Above-zone; Active

Matching Parameters	
S (øhct)	0.0000312
T (kh/μ)	222922