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Development of Improved Caprock Integrity and Risk Assessment Techniques

Project Number (FE0009168)

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U.S. Department of Energy

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Developing the Technologies and
Infrastructure for CCS

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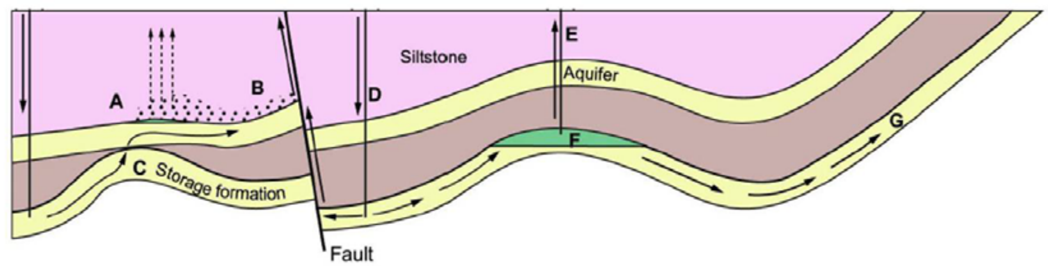
Introduction and Motivation

A primary requirement for long-term geologic storage and containment of carbon dioxide is ensuring caprock integrity. Large-scale CO2 injection requires improved and advanced simulation tools and risk assessment techniques to better predict and help control system failures, and to enhance performance of geologic storage.

GeoMechanics Technologies is developing enhanced simulation and risk analysis approaches to assess and control geomechanics-related system failures (induced fracturing, faulting, bedding plane slip, or permeation through natural fractures and faults) at geologic carbon storage sites.

Sample gas storage leakage pathways.



Matrix

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

Structural

- Flow on faults
- Flow on fractures
- Flow on hydraulic fractures
- Flow between permeable zones due to juxtapositions
- Fractured shales

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

From Nygaard, 2010

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Benefits to the Program

<u>The anticipated benefits to CCUS of the proposed work include</u>:

- Providing a more expansive and detailed review and analysis of historical caprock integrity problems and incidents encountered by the gas storage and oil & gas injection industries. These data can be used by other researchers to inform, compare, and validate alternative techniques for caprock integrity analysis and simulation;
- Development and description of an improved combined transport modeling and geomechanical simulation approach to predict and assess caprock integrity, with documented application to a wide range of geologic settings and operating conditions, including actual case histories;
- Development and description of a quantitative risk assessment tool to help identify and mitigate caprock integrity problems, which is needed for the implementation of large-scale CCUS projects.

This project addresses program goals to ensure 99% storage permanence, containment effectiveness, and best practices for characterization and risk assessment.

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Project Overview

The objectives of this project will be achieved through a combined research and analysis effort that includes:

1. Review and analysis of historical caprock integrity problems in gas storage industry.

2. Development and description of improved theoretical approaches to assess caprock integrity for a range of geologic settings;

3. Development and demonstration of advanced geomechanical simulation techniques to predict caprock integrity problems, and provide operating guidelines;

4. Development of a quantitative risk assessment tool for caprock integrity;

5. Application and demonstration of the geomechanical simulation and risk assessment techniques to several historical and potential storage operations; and,

6. Documentation of practical recommendations and guidelines for caprock characterization and operating practices to reduce caprock integrity damage risks.

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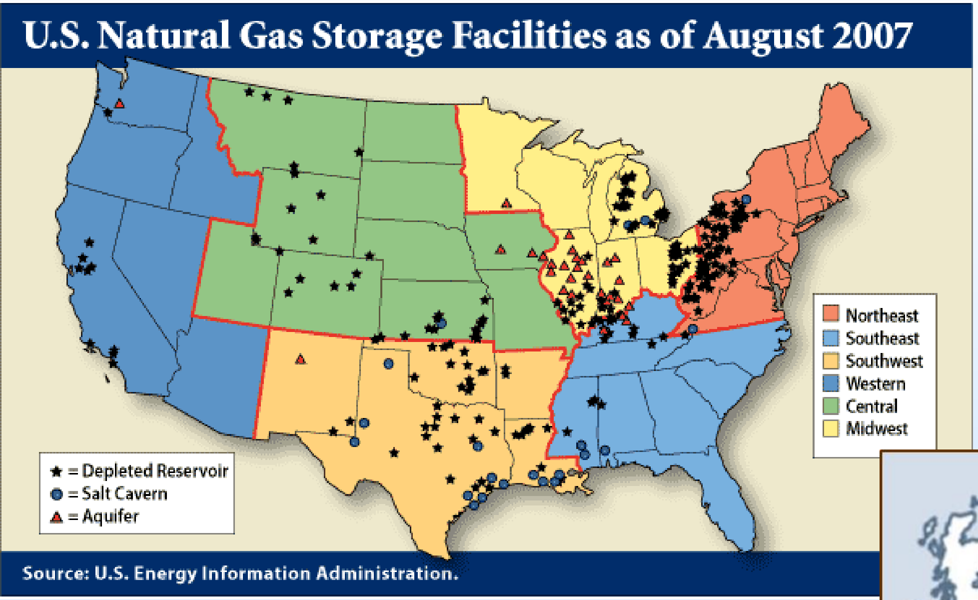
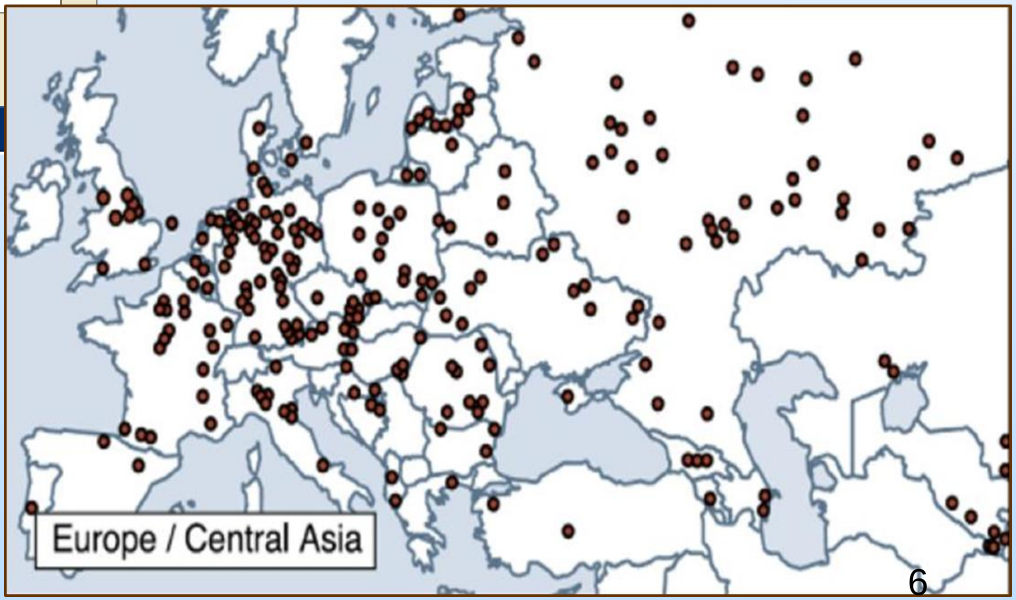
Historical Data Review in Gas Storage Industry



IEAGHG (2009)



UGS sites in the Europe and Central Asia

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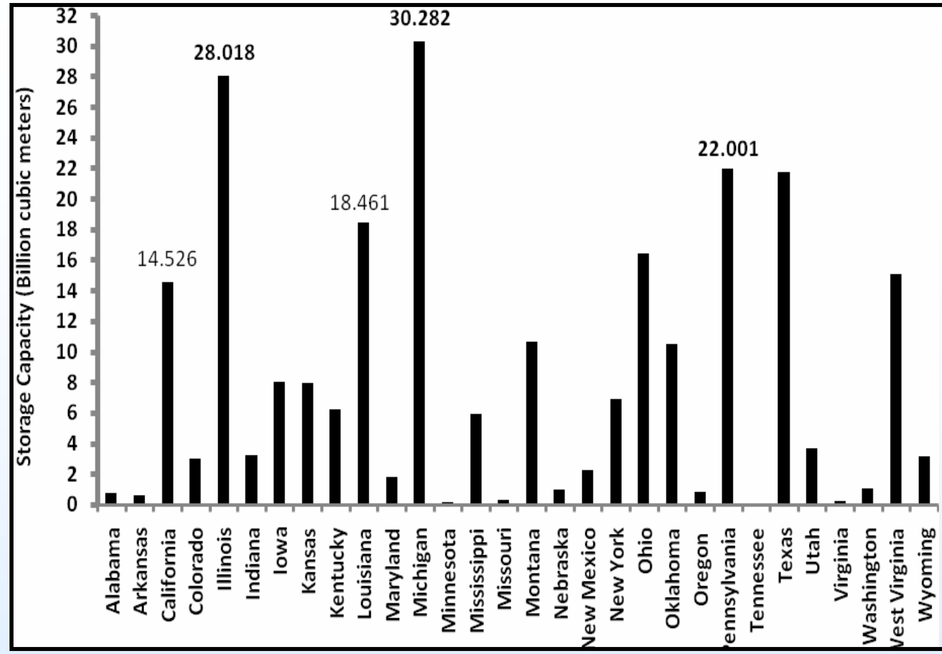
Overview of Underground Gas Storage:

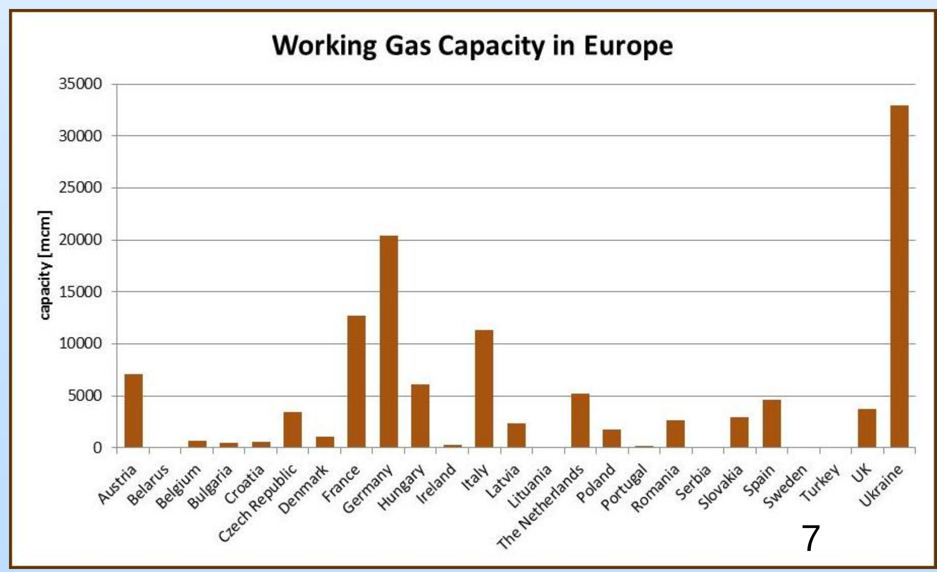
- Underground Fuel Storage (UFS) began in 1915
- As of 2005, For **U.S.** UGS:
  - 410 UGS facilities total
  - 330 in Depleted O&G Fields
  - 43 in Aquifers
  - 37 in Salt Caverns
  - < 1% in mines
- As of 2012, For **European** UGS:
  - 155 UGS facilities total
  - 82 in Depleted O&G Fields
  - 30 in Aquifers
  - 39 in Salt Caverns
  - 2 in mines

EIA, 2006



Working Gas Capacity by States in U.S.

GIE, 2012



Working Gas Capacity by Country in Europe

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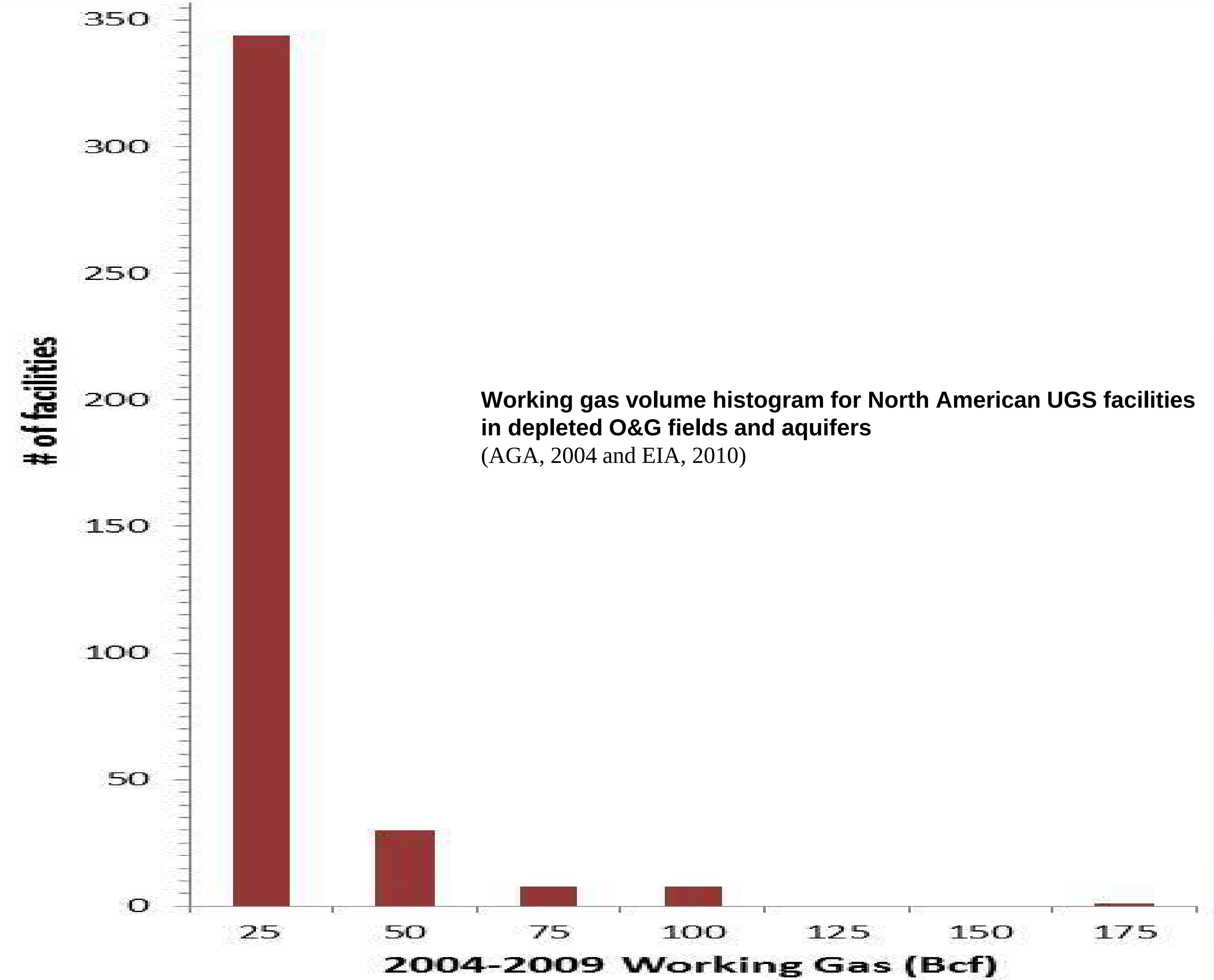

Working gas volume histogram for North American UGS facilities in depleted O&G fields and aquifers
(AGA, 2004 and EIA, 2010)

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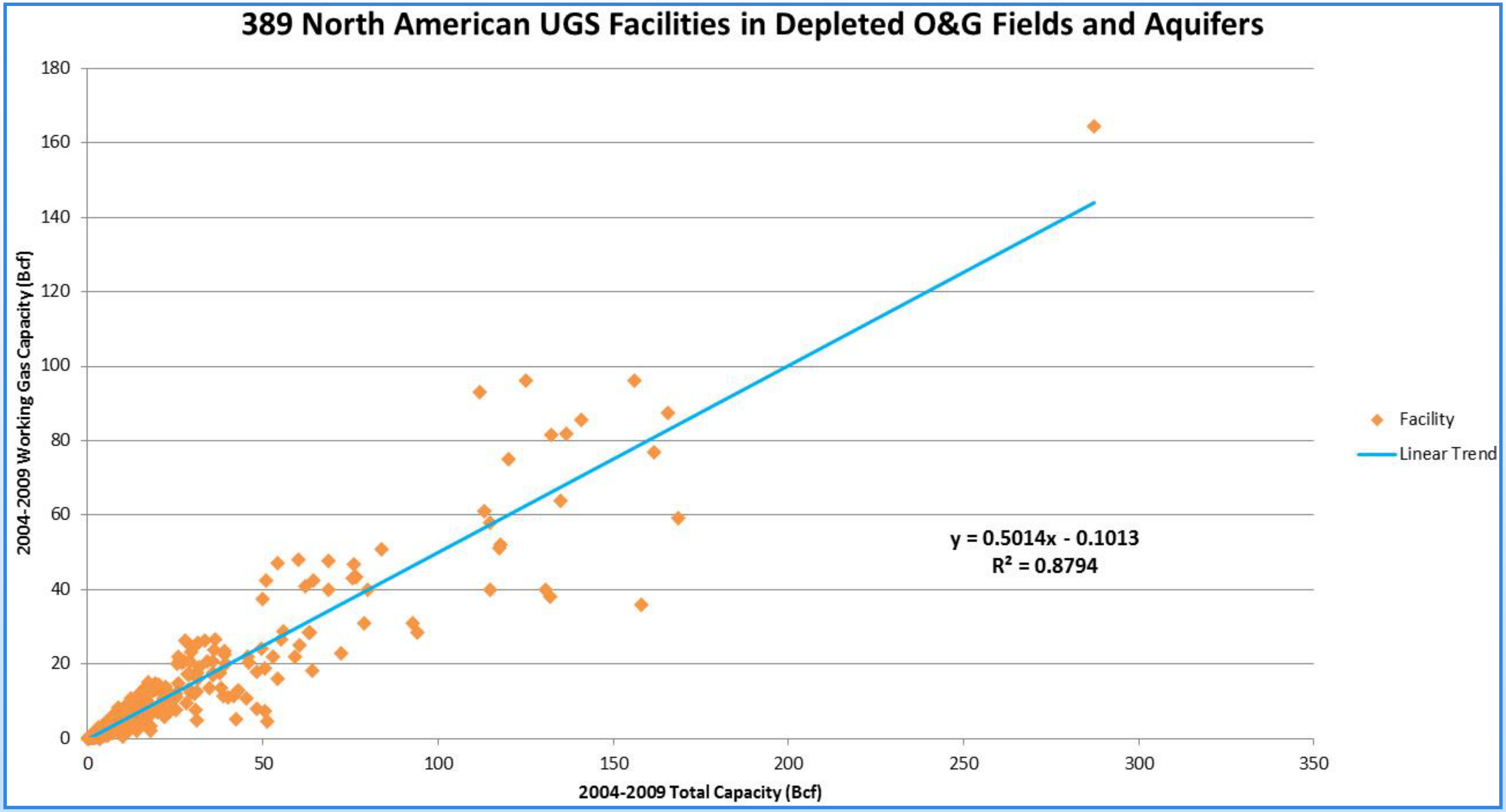

Scatterplot comparing working gas to total gas capacity for North American UGS facilities in depleted O&G fields and aquifers
(AGA, 2004 and EIA, 2010)

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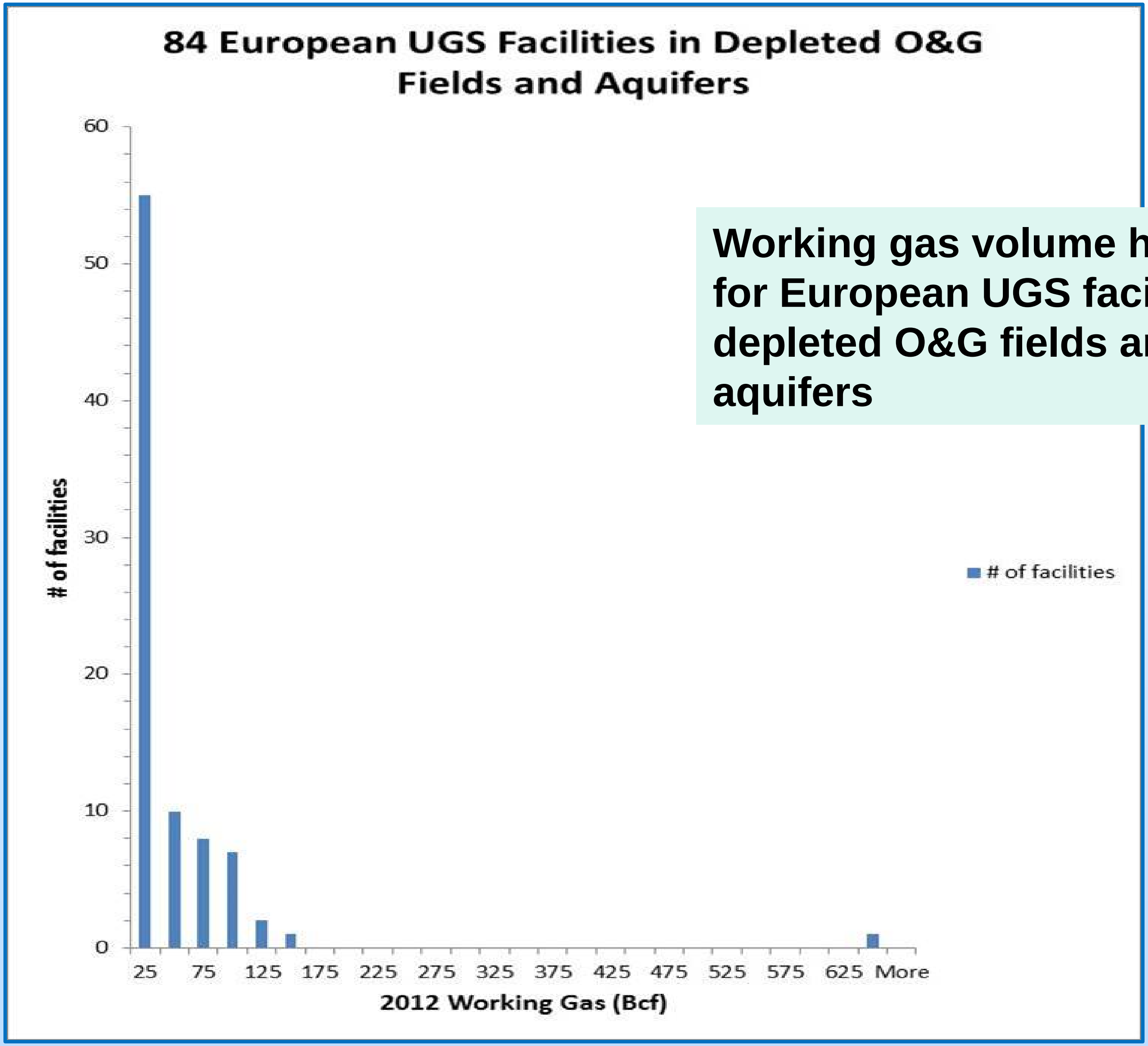
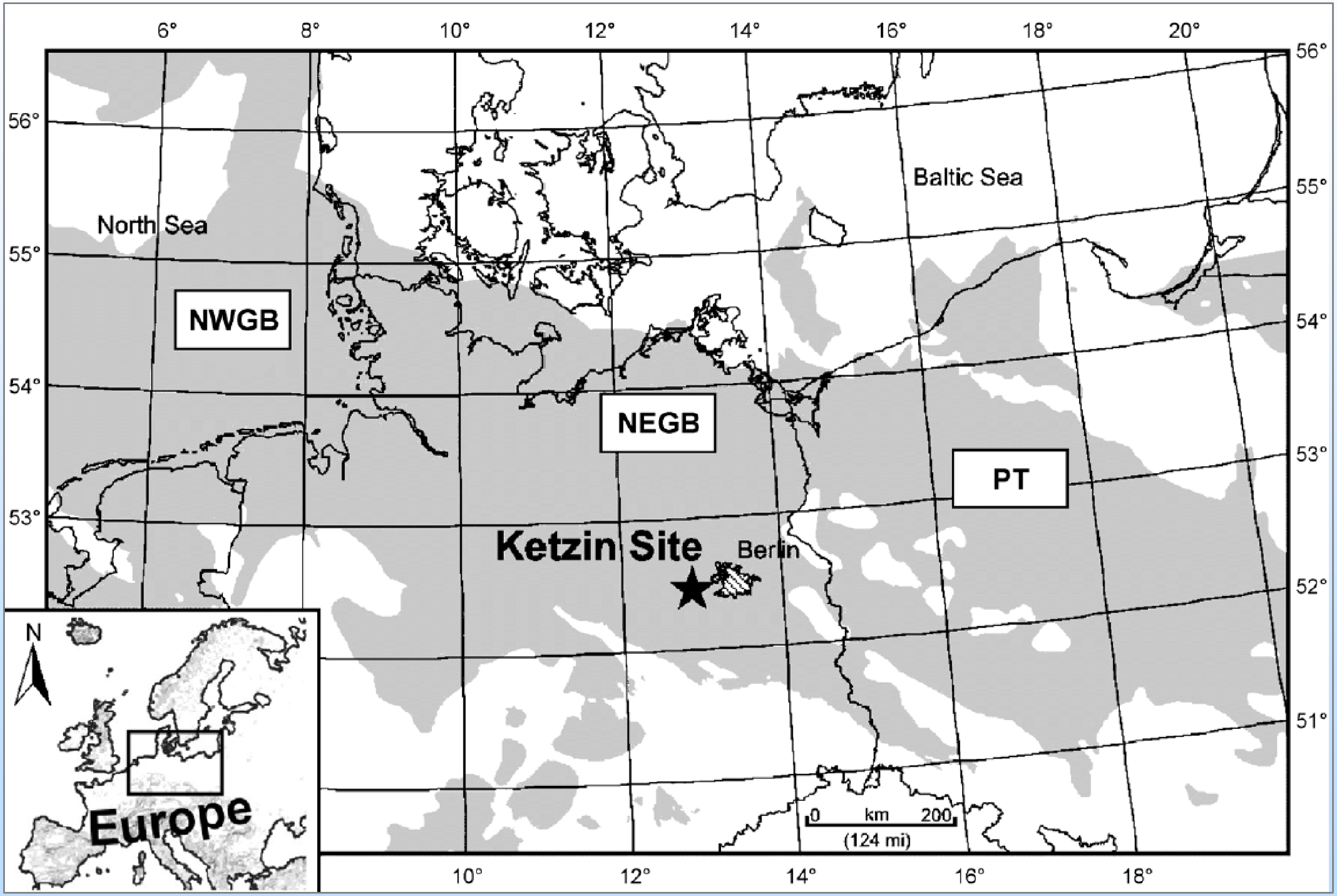


Working gas volume histogram for European UGS facilities in depleted O&G fields and aquifers

Ketzin



Permian Basin (grey), with Northeast German Basin (NEGB)
(Förster et al, 2006)

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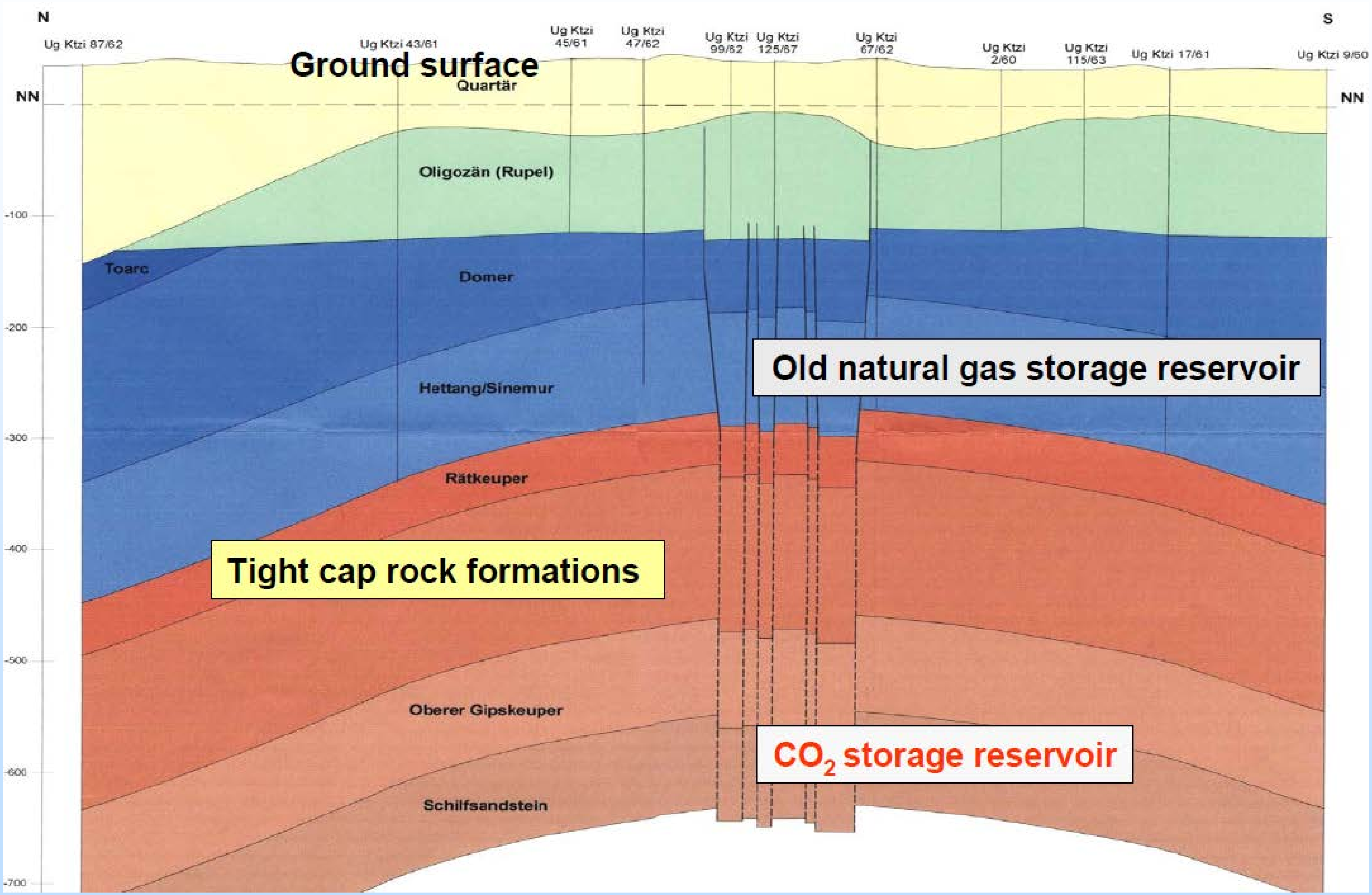
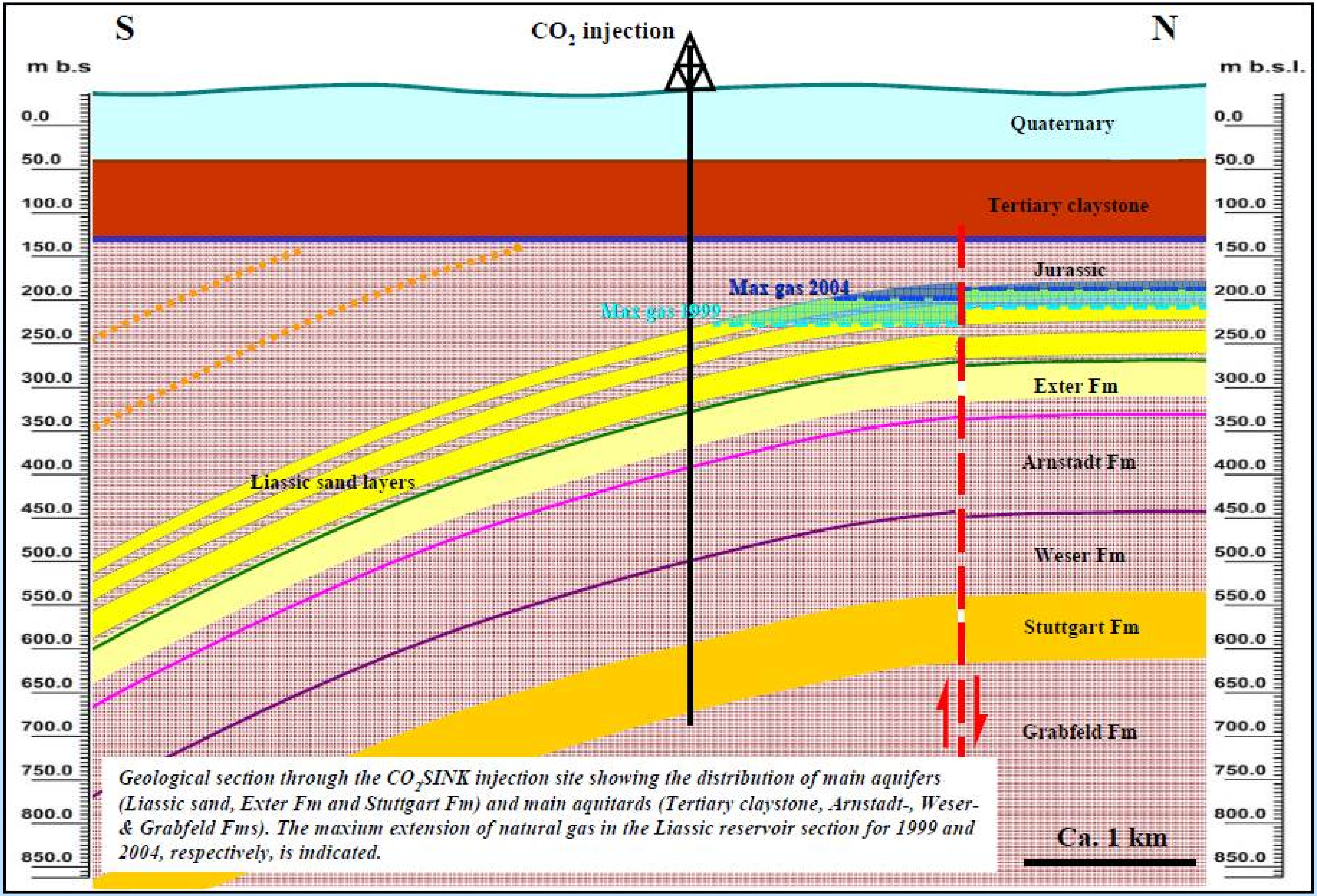


Geologic cross section through Ketzin Anticline, showing normal faulting in anticline crest
(Christensen, 2004)



UGS cross section of maximum gas distribution in 1999 and 2004

Note that the shown fault would be the furthest south normal fault in the CGFZ (Schilling, 2007)

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Loudon & Illinois Basin

STRATIGRAPHIC COLUMN LW8 WELL VICINITY

AGE	LITHOLOGY	FORMATION	THICK average	DESCRIPTION depth @ LW8 well
Quat.			75 ft	Glacial drift
Pennsylvanian			1025 ft	Undifferentiated sandstones, shales and limestones. Lie unconformably under the glacial drift.
Mississippian		Chesterian Series Formations	520 ft	Sandstones, limestones and shales. Including the productive sand reservoirs of Tar Springs Fm, Cypress Fm, Weiler Mbr, Paint Creek Fm, Bethel Mbr,
		Aux Vases	50 ft	Sandstones, productive sand reservoir
		Ste. Genevieve St. Louis	370 ft	Tight limestones and dolomitic, some anhydrite
		Salem	90 ft	Oolitic limestones 14% porosity, 77 md permeability
		Warsaw	90 ft	Limestones, fossiliferous,
		Borden/Osage	645 ft	Shales, siltsones and Carper Sand. Siltsone tight w/poor porosity and perm. @ 2171-2752' Productive Carper Sand, 16' thick @ 2752-2768', must be frac. to produce Basal siltsone @ 2768-2805'
		Chouteau	11 ft	Dense argillaceous limestone @ 2805-2816'
Devonian		Maple Mill New Albany	110 ft	Shales @ 2816-2926', natural fractures present, New Albany shales rich in organic content, gas produced is indigeneus
		Cedar Valley	85 ft	Dense, crystalline lm, fossiliferous, some calcerous sd & slt beds @ 2926-3008'
		Grand Tower	65 ft	Dolomite vuggy & fossiliferous, 16% porosity, up to 1D perm. @ 3008-3071'. Consists of U. Jeffersonville & L.. Geneva dolomite & Dutch Creek sd
Silurian		Waukesha	350 ft	Dense dolomite, parts have intercrystalline to vuggy porosity, Lie unconformably under Grand Tower
			180 ft	Limestones

Oil producing
Gas producing
unconformity
sandstones
Limestones
siltstones
dolomites
glacial drift
shales

Source: GRI, 1994, Humble, 1963, court dockets

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U.S. UGS Leakage Events:

Modified from Evans (2009)

Contributory processes/mechanisms attributed to leakage/failure	Storage Facility Type		
	O&G Fields	Aquifers	Totals
Migration from Injection Footprint/Cavern (not Due Entirely to Well Problems)	11	13	24
Caprock - Not Gas Tight/Salt Thick Enough	3	12	15
Caprock - Fractured/Faulted, Not Gas-Tight	4	5	9
Seismic Activity	1	0	1
Not Available	4	1	5

- ~373 US UNGS facilities operational and abandoned in O&G fields and aquifers
- 28 of these reservoirs have experienced leak incidents
- 28/373 = 7.5% incident rate

European UGS Leakage Events:

Evans (2009)

Storage Facility Type					
Country	Depleted field	Aquifer	Salt Cavern	Mine/ Rock Cavern	Total
Russia			6		6
France		1	3		4
Germany	1	4	2		7
Poland		1			1
Hungary		1			1
Belgium				1	1
Denmark		1			1
Finlang				1	1
GB&Ireland	2		1		3
Sum	3	8	12	2	25

- ~112 European UGS facilities operational and abandoned in O&G fields and aquifers
- 11 of these reservoirs have experienced leak incidents
- 11/112 = 9.8% incident rate

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Some Key Points to Consider

1. Reported and documented incidents are not comprehensive. Most leakage incidents are not documented. During the past five years GeoMechanics has been involved in half a dozen legal disputes involving storage gas migration which are not documented or mentioned in literature.
2. The natural gas storage industry has a strong economic incentive not to lose gas. Yet it does not achieve 99% containment over decades.
3. 99% containment over 100 years is a goal, not a likely outcome.
4. Leakage out of zone generally does not result in leakage to surface. Overburden characterization is a key component of risk assessment.

Risk Cost = Probability x Consequences

Finally: ***Yesterday's Caprock is Today's Shale Gas Play***

What about tomorrow ?

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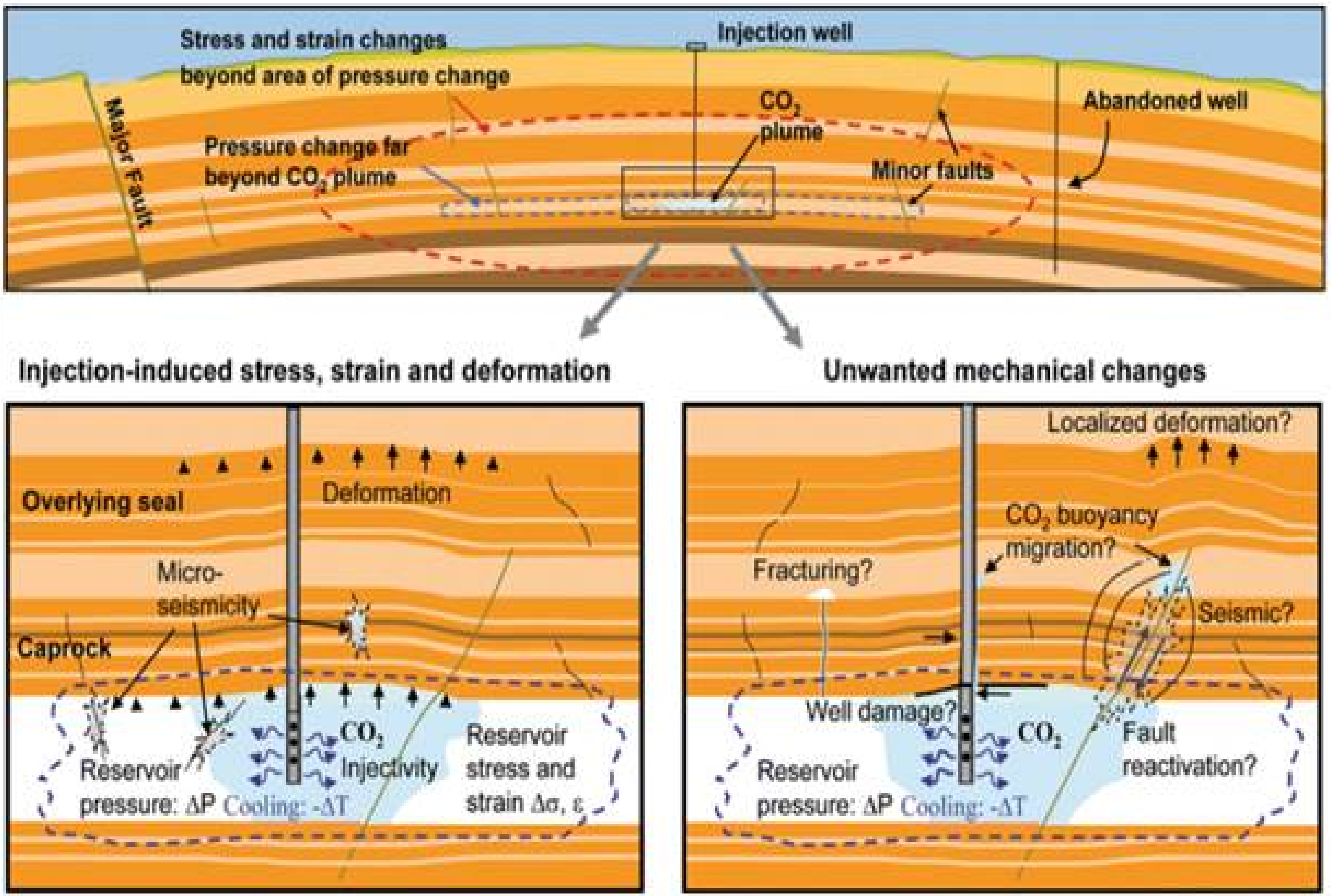
Geomechanical Processes Associated with Geologic Sequestration of CO_2

Rutqvist (2012)



Analytical Equations for Induced Shear Stresses

The volumetric strain of a reservoir element, $\Delta V/V$, depend on the change in pore pressure times the reservoir material compressibility, C_b.

$$\Delta V/V = C_b \Delta P + 3\alpha\Delta T$$

Total induced shear stresses caused by a varying pressure within an arbitrarily shaped reservoir can be obtained by integrating the contribution of all these expansion points over the reservoir volume, V as follows:

$$\tau_{yz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial y \partial z} + 2z \frac{\partial^3 V_2}{\partial y \partial z^2} + \frac{\partial^2 V_2}{\partial y \partial z} \right] dV$$

$$\tau_{xz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial x \partial z} + 2z \frac{\partial^3 V_2}{\partial x \partial z^2} + \frac{\partial^2 V_2}{\partial x \partial z} \right] dV$$

The expression τ_{xz} and τ_{yz} are the horizontal shear stresses at position (x_0, y_0, z_0). E_0 is the Young's Modulus for the overburden material and v is the Poisson's ratio. V_1 and V_2 are distance functions given by:

$$V_1 = \frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}}$$

$$V_2 = \frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z+z_0)^2}}$$

Analytical Models for Caprock Integrity

Illustration of a typical distribution of shear stresses at the reservoir caprock interface. Shear stresses are normalized with respect to reservoir radius, height, and material properties for assumed reservoir pressure change which varies linearly with radius, from r = 0 to r = R, in an axisymmetric reservoir of outer radius R.

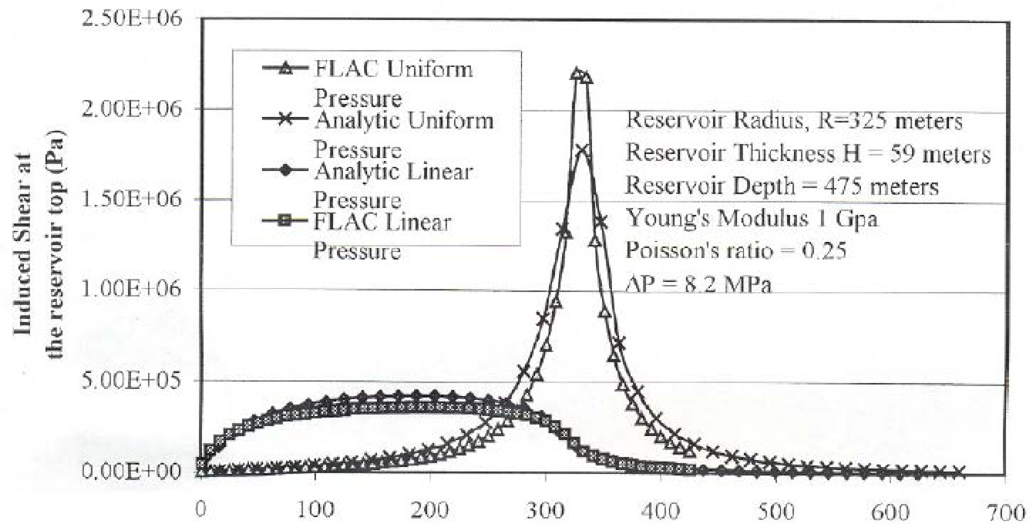


Figure 3. Comparison of induced shear stresses for cases with linear and uniform pressure gradients.

Bruno et. al (1998)

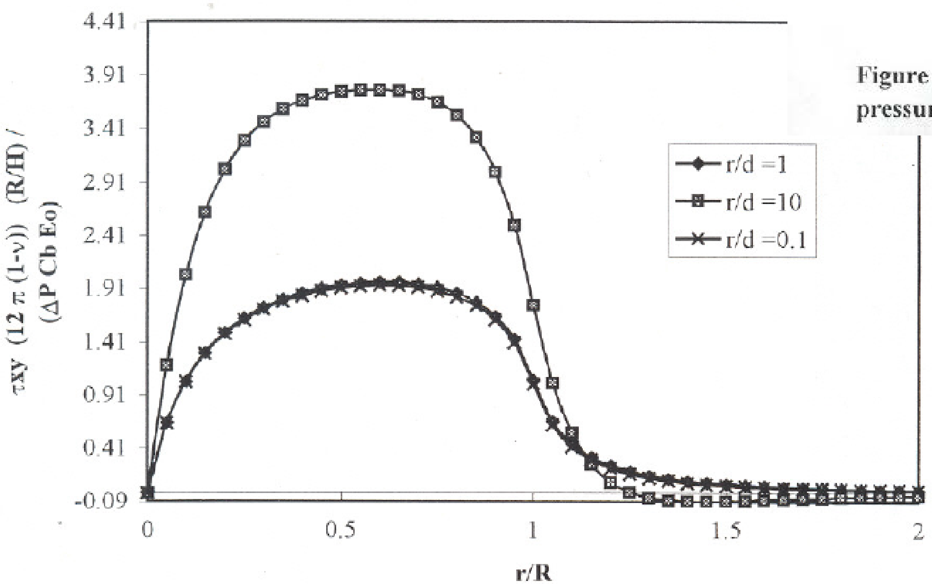
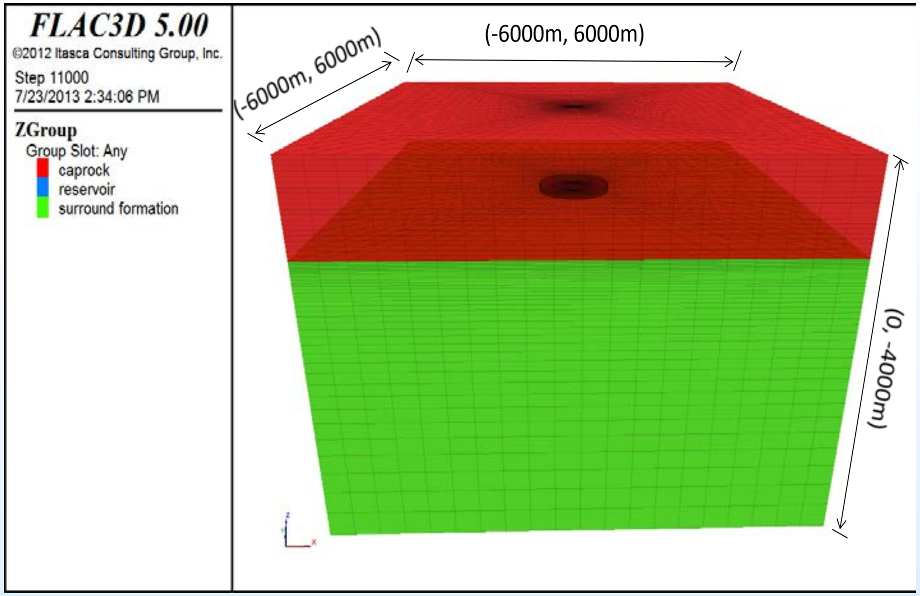


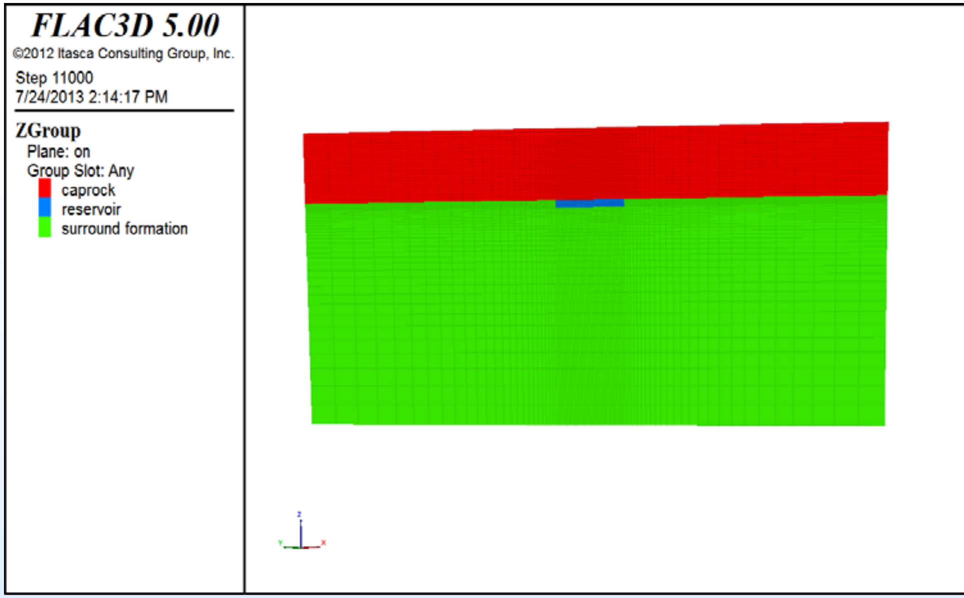
Figure 2. Normalized shear stresses at the top of an axisymmetric reservoir with linear pressure gradient.

$$\tau_{yz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial y \partial z} + 2z \frac{\partial^3 V_2}{\partial y \partial z^2} + \frac{\partial^2 V_2}{\partial y \partial z} \right] dV$$

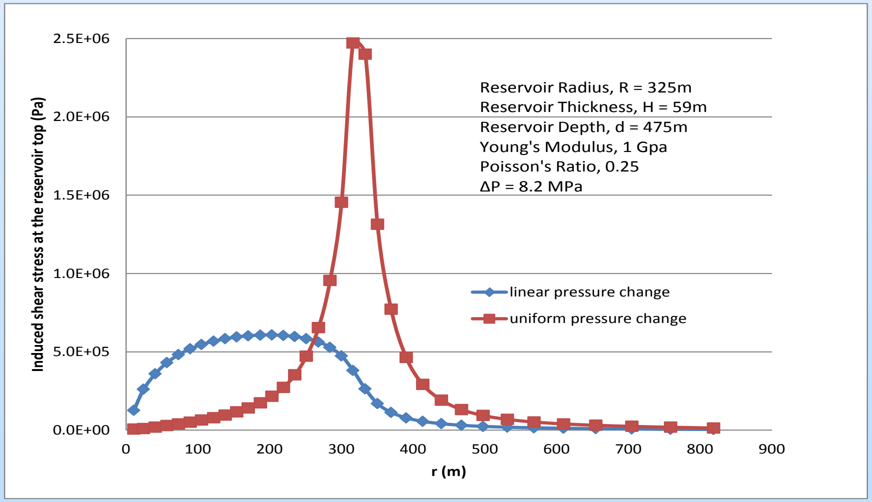
$$\tau_{xz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial x \partial z} + 2z \frac{\partial^3 V_2}{\partial x \partial z^2} + \frac{\partial^2 V_2}{\partial x \partial z} \right] dV$$

Numerical Model for Caprock Integrity Study

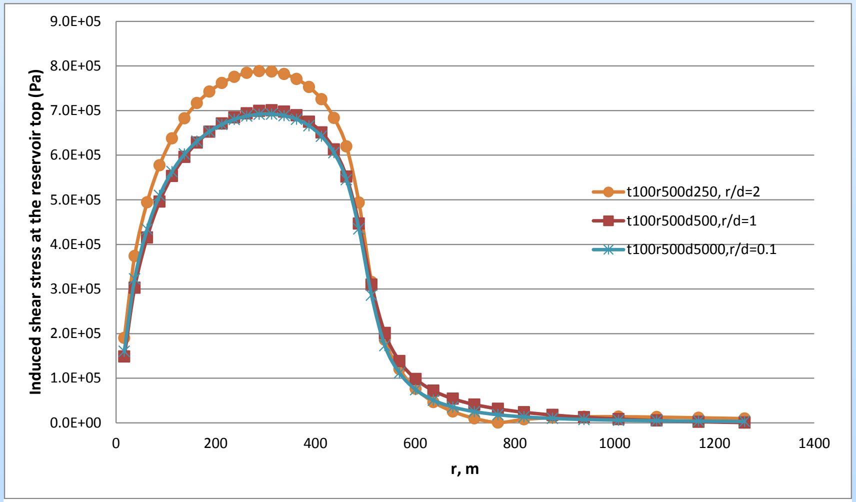




(Left) 3D geomechanical model used to study induced shear stress in caprock; (Right) Section view through center of model.



Comparison of induced shear stress with linear (blue) and uniform (red) pressure change.



Induced shear stress in the caprock for the same reservoir shape, while changing the reservoir depth, with linear pressure change in the reservoir.

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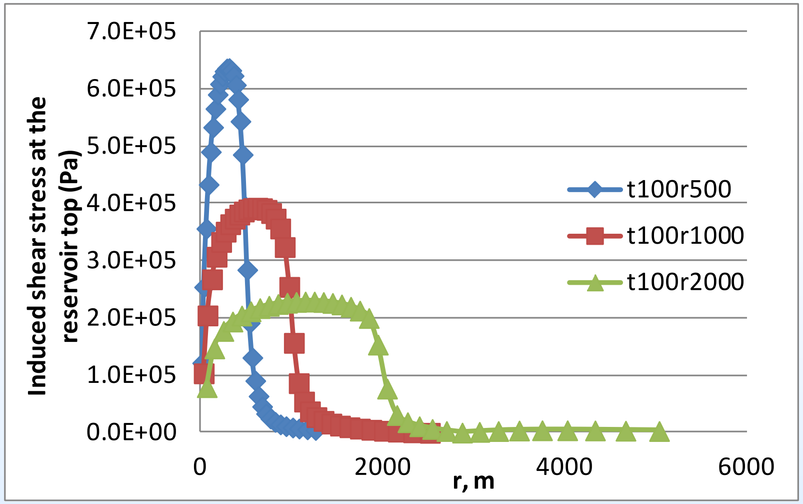
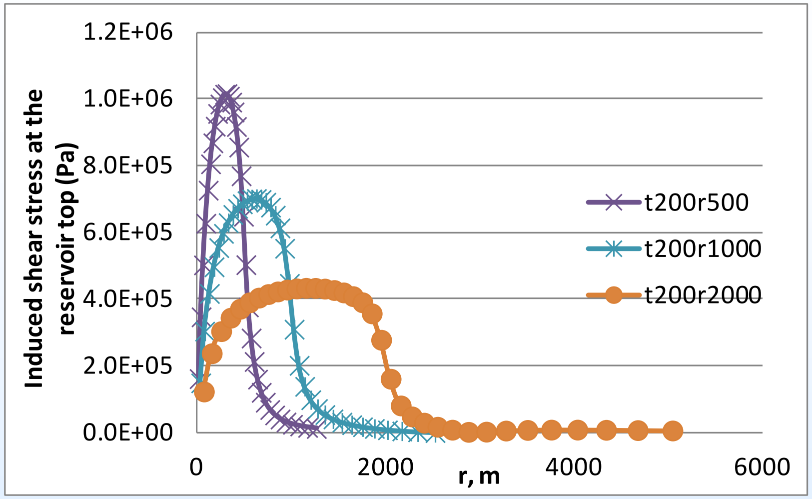
Varying Reservoir Thickness & Radius

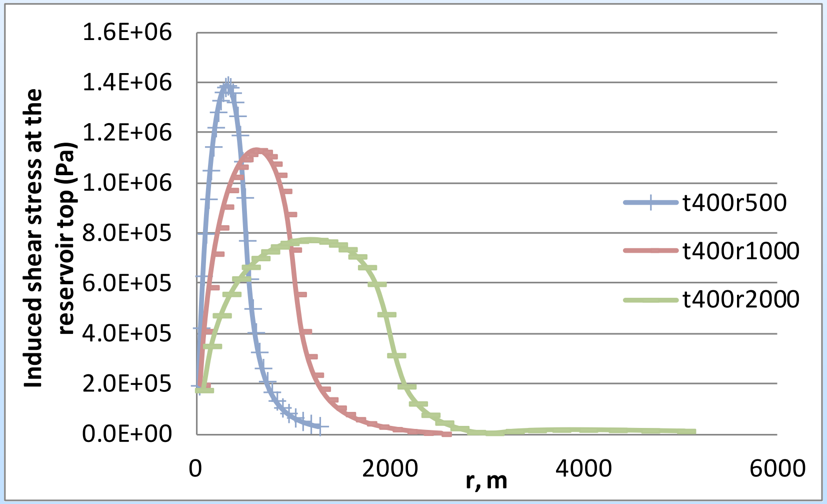
(a)



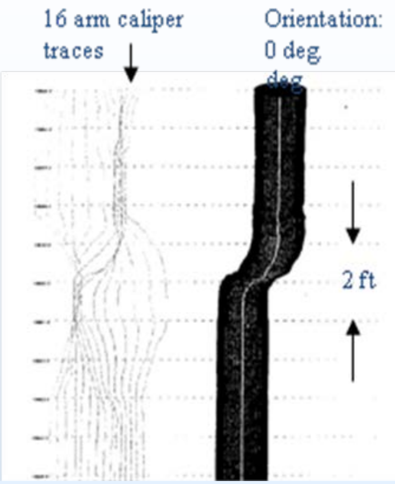
(b)

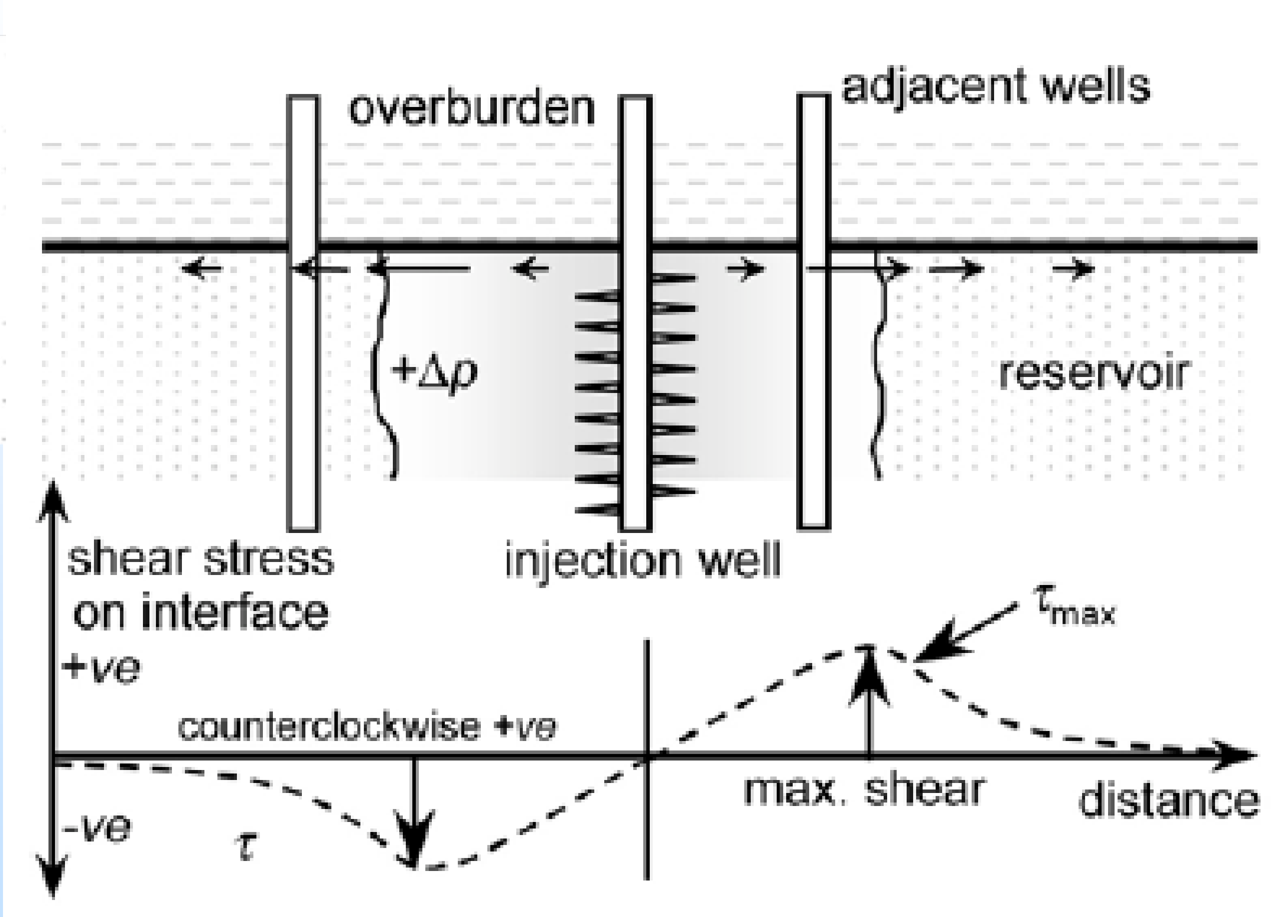


(c)



Induced shear stress in the caprock with (a) 100m, (b) 200m, and (c) 300m reservoir thickness while changing reservoir radius from 500m to 2000m under linear pressure change.





Fluid injection causes lateral expansion of the injection interval, inducing shear stresses (and possible bedding plane slip) at the top of the injection interval. Well image in upper left shows typical localized deformation imparted to casing above a gas field.

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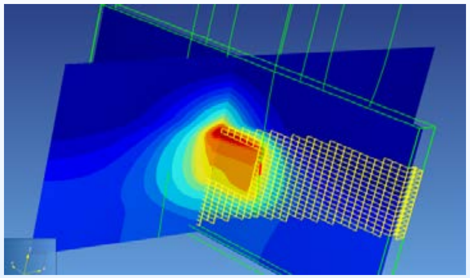
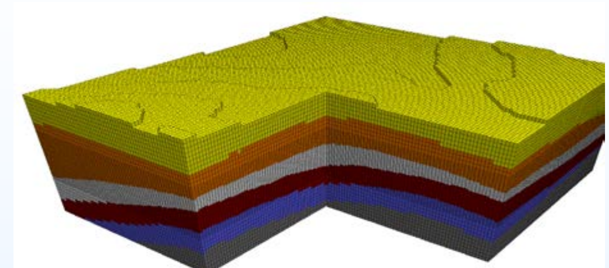
Our focus has been on developing tools to create consistent and integrated models of geologic conditions, geomechanical processes, and fluid and heat flow processes.





Geologic Modeling

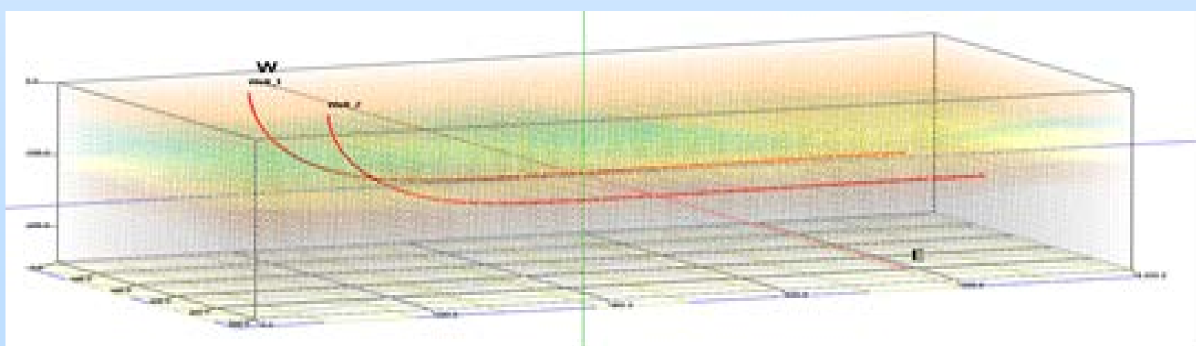
- Rockworks
- Petrel
- Paradigm
- GeoGrid

Fluid Flow Simulation ⇔ 3D Data Translation and Transfer ⇔ Geomechanics Simulation

- Tough2
- Tetrad
- Eclipse

Visualization and Graphical User Interface

- GeoMech
- Flac3D
- Abaqus
- GeoFrac



GeoMech3D^{TM} Software System Developed and Applied by GeoMechanics

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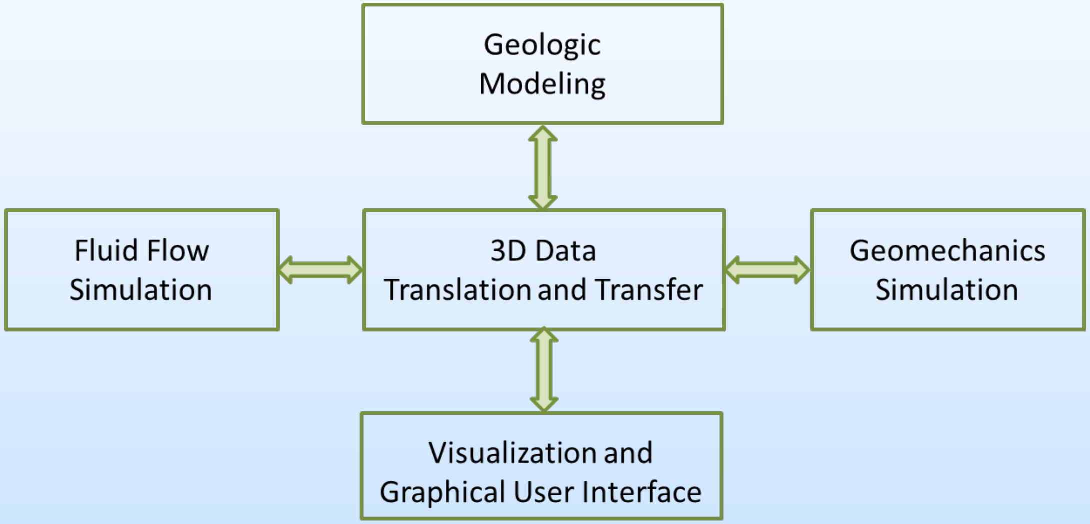
Numerical Analyses of CO2 Storage Operations:

1. Wilmington Graben CO2 Site
2. Kevin Dome CO2 Site
3. Louden Field

Includes:

- 3D Geology Model
- 3D Fluid Flow Simulation
- Geomechanical Simulation



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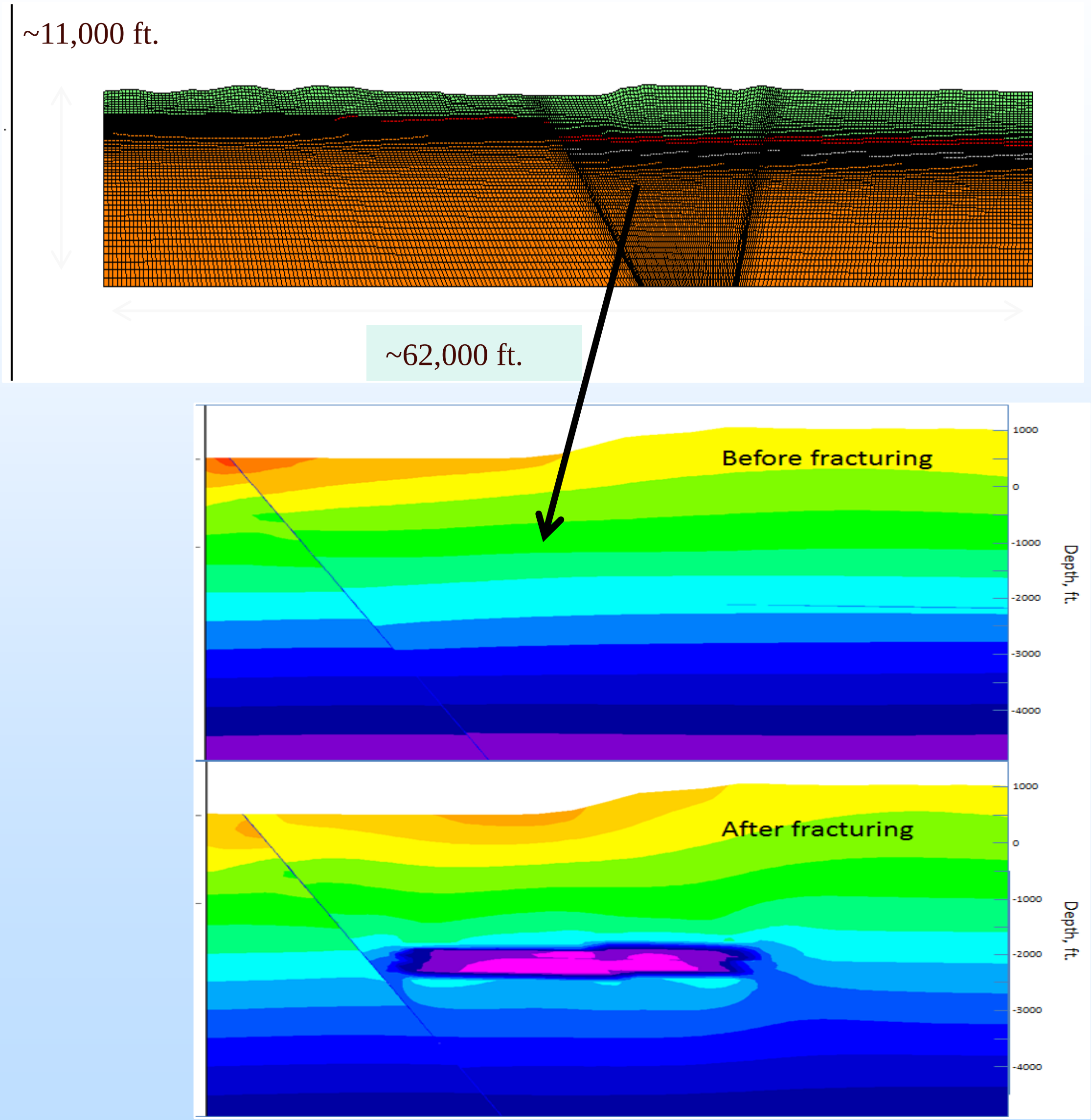

Fault Activation Comments:

1. Injection near normal faults typically acts to increase stability
2. Injection near reverse faults typically acts to decrease stability
3. But, it is also important to consider possible pore pressure increase within fault plane.
4. 3D geomechanical modeling can be applied to estimate extent of fault movement

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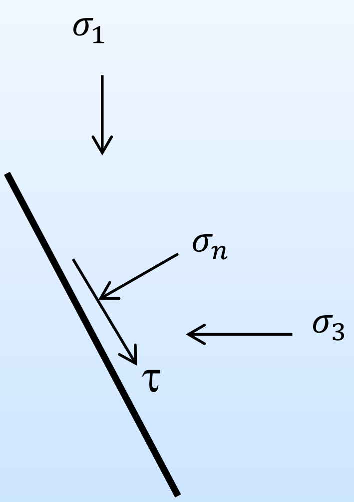
Shallow shale formation example

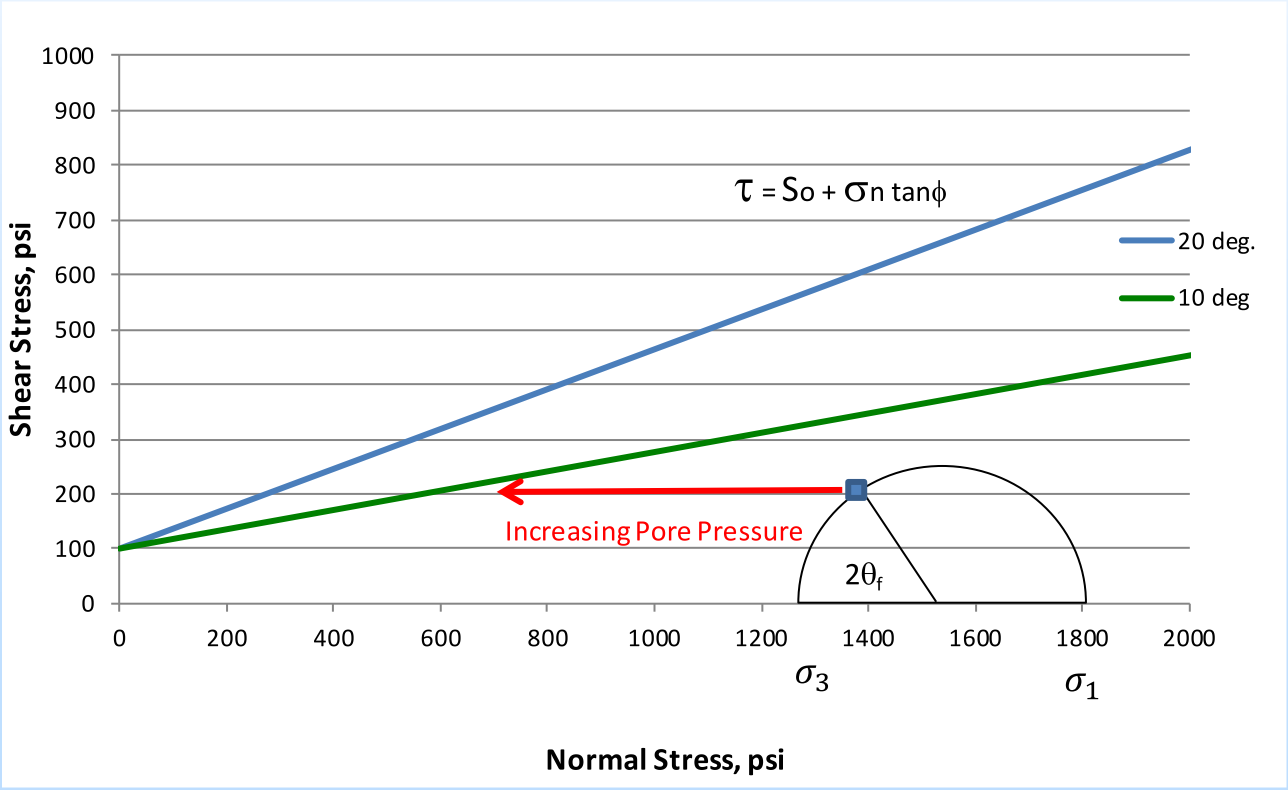
σ_1 eff = 1.1(2700) - 0.43(2700) = 1809 psi

σ_3 eff = 0.9(2700) - 0.43(2700) = 1269 psi

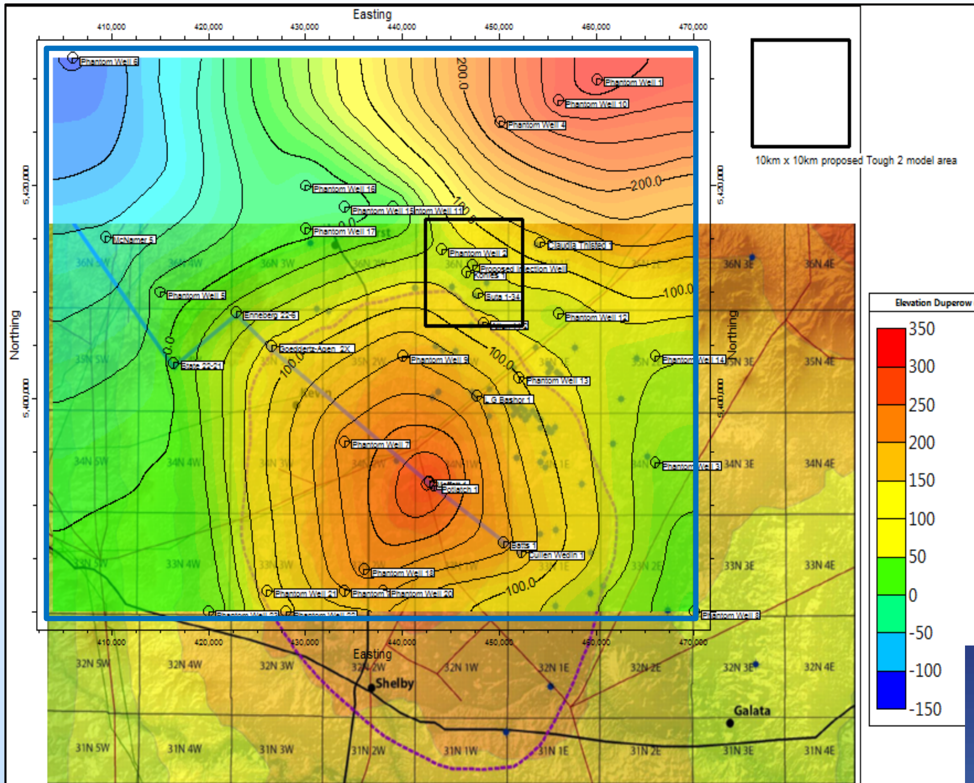
τ max = 270 psi

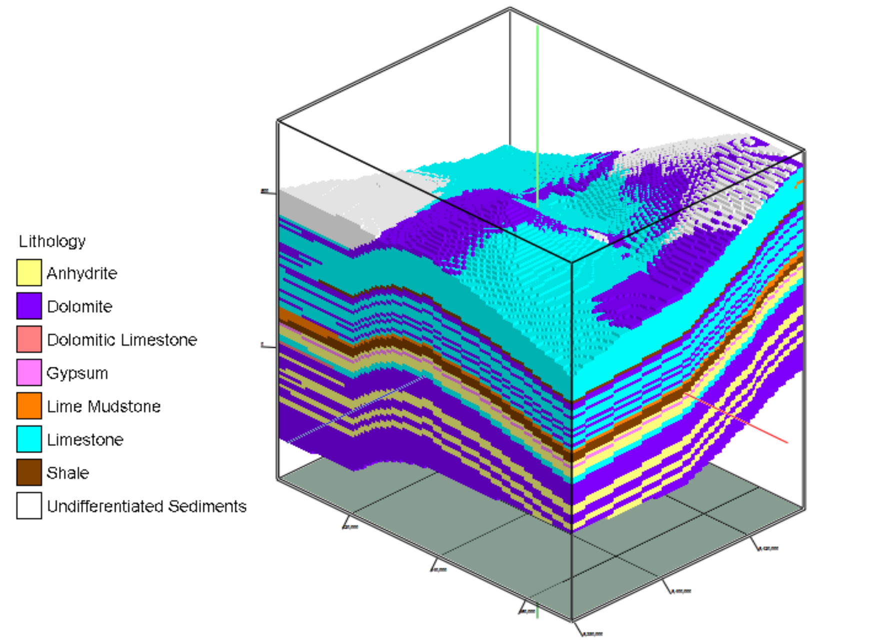
Pore pressure influence on fault activation

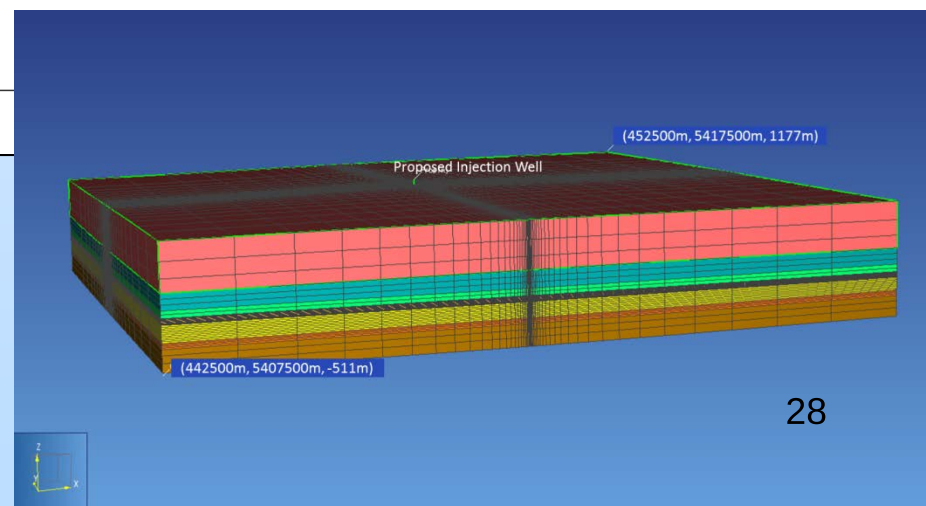




3D Fluid Flow and GeoMechanical Model for Kevin Dome

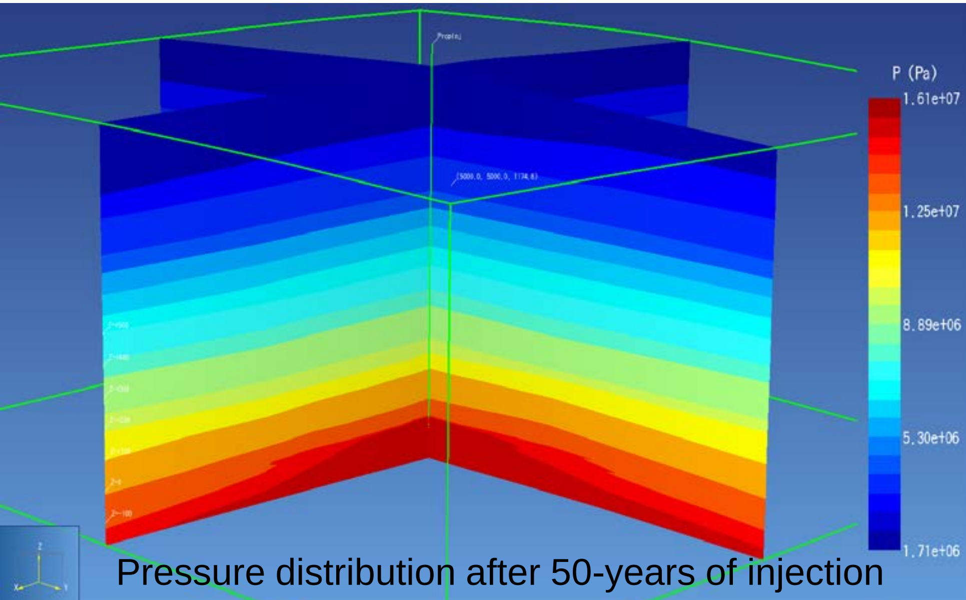




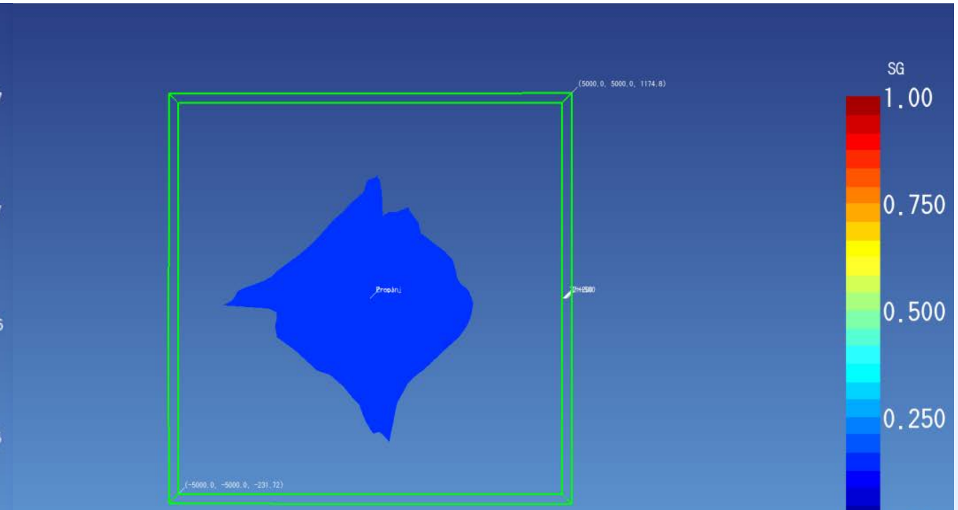


(Top Left) Blue box marks perimeter of the geologic model boundary. Black box indicates location of the 10km by 10km Tough2 model boundary; (Top Right) Geologic model; (Bottom Right) Tough2 model.

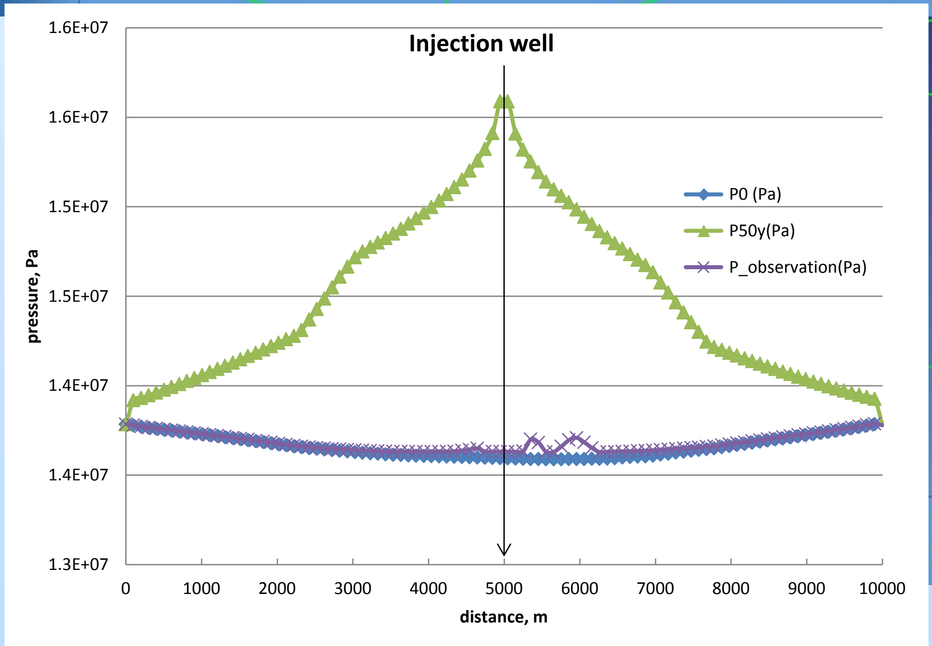
3D Fluid Flow Model Results for Kevin Dome

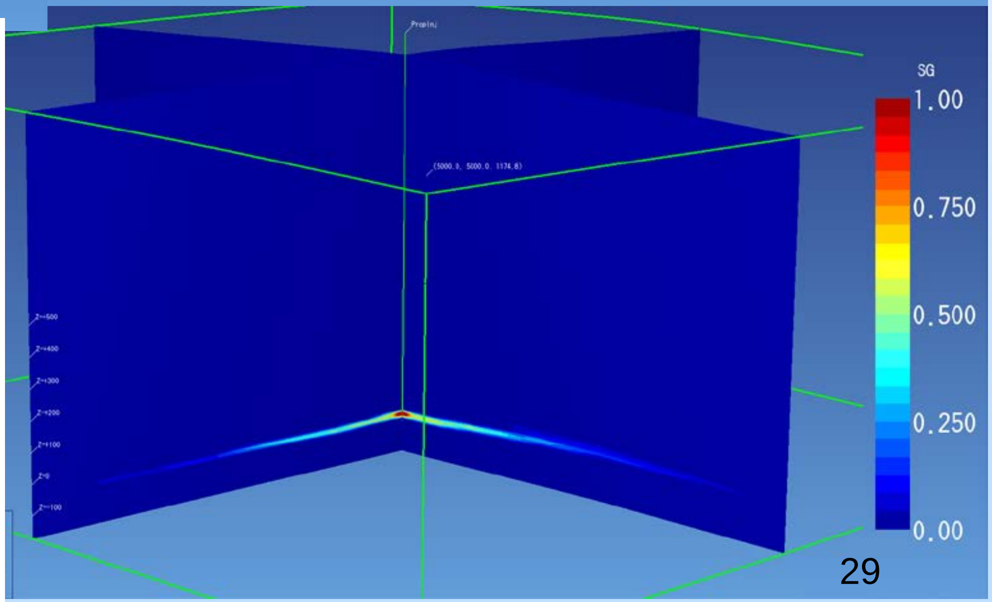


Pressure distribution after 50-years of injection



CO2 gaseous plume after 50 years of injection

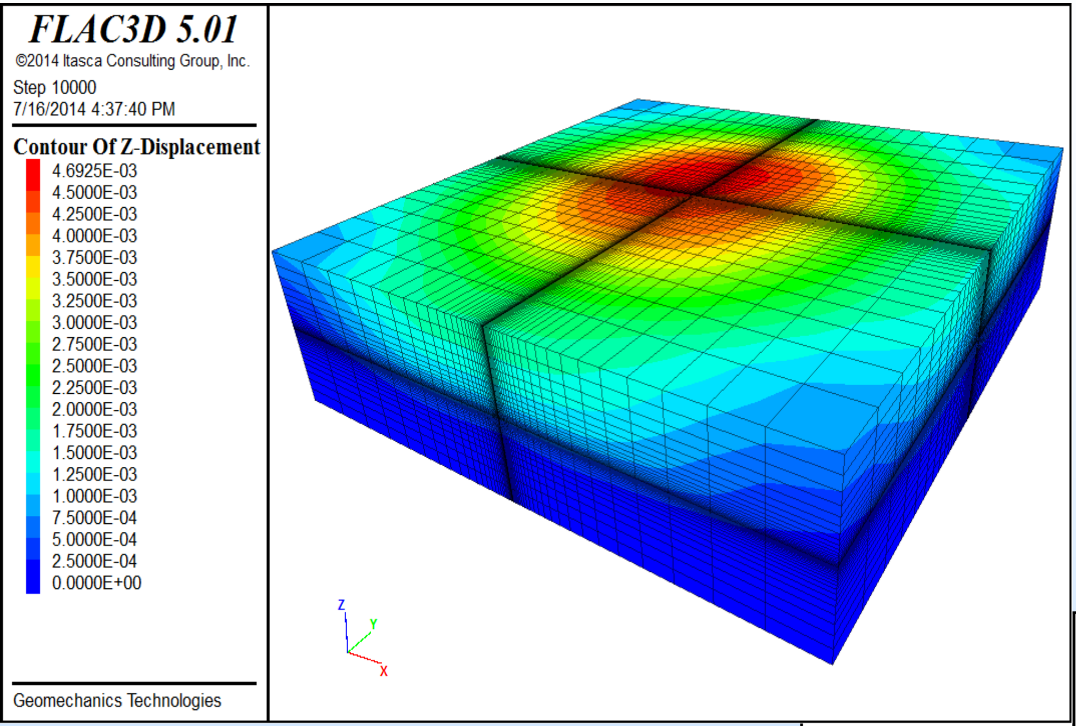


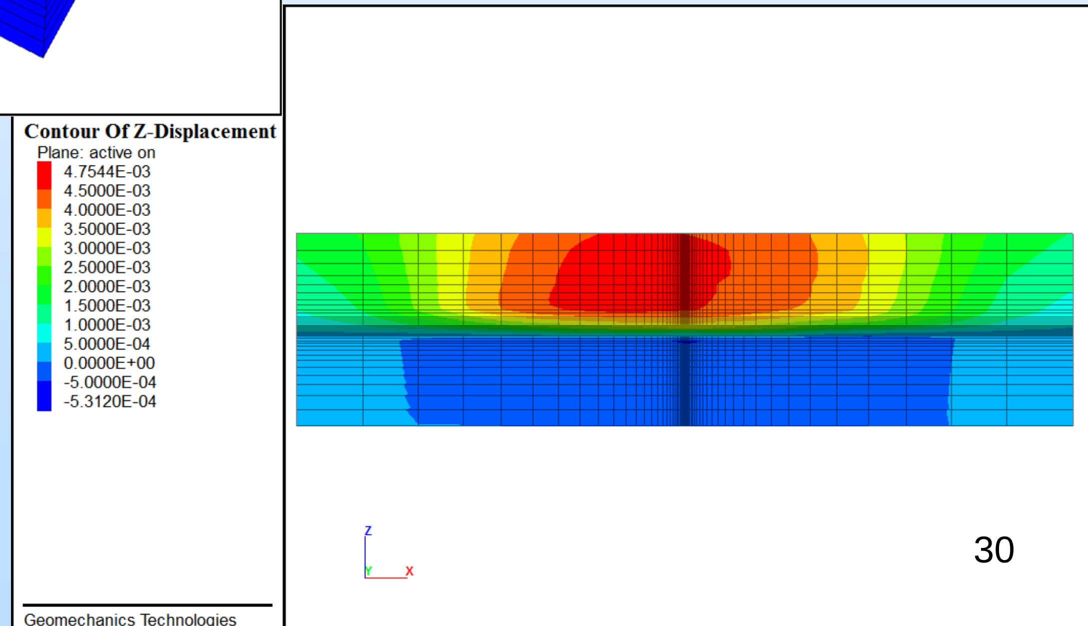


t = 50 years

3D Geomechanical Model Results for Kevin Dome

Induced vertical displacement (meter) 3D view through the injection well in E-W direction





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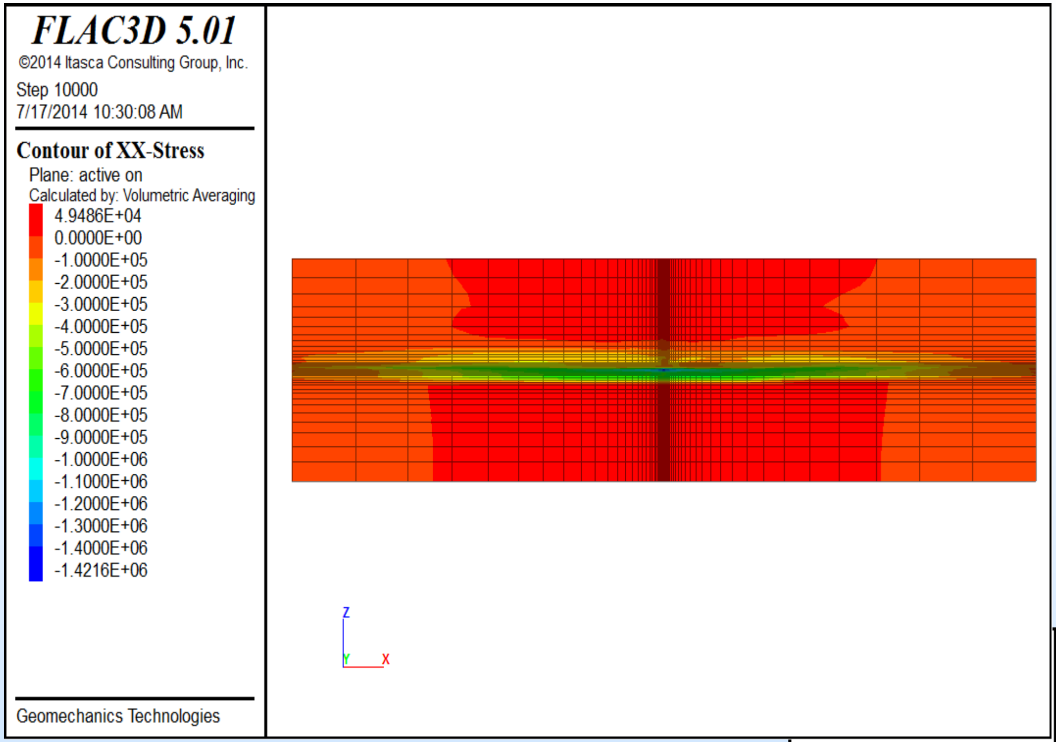
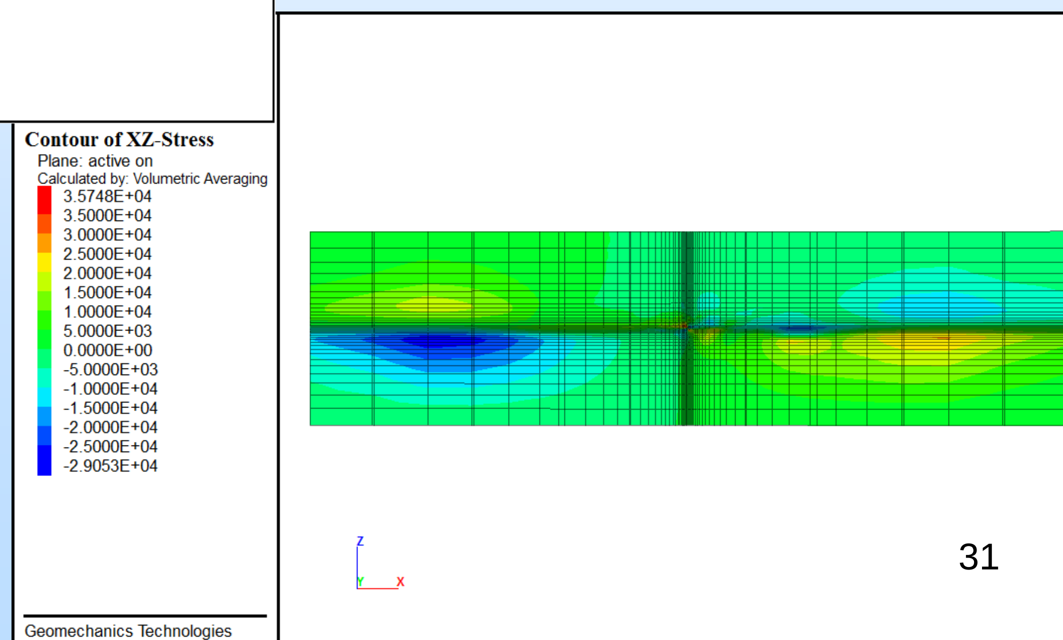


Induced horizontal xx-stress (Pa) & horizontal shear xz-stress (Pa) through the injection well in E-W direction



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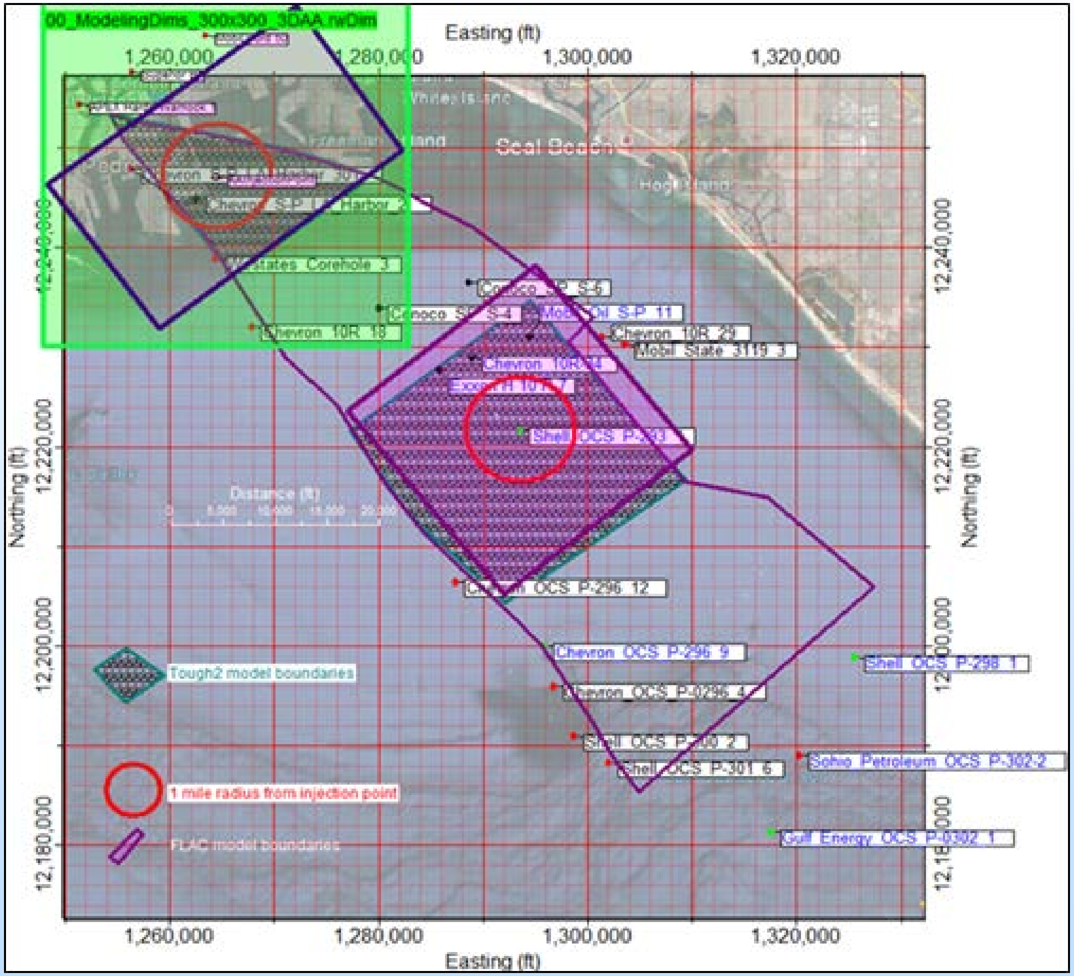
3D Fluid Flow and GeoMechanical Models for Caprock Integrity



Map of Wilmington Graben Characterization Project located offshore near Long Beach, California.

Developed Geologic, Fluid Flow and Geomechanical Models for the Graben Areas

Apply Geomechanical Model to assess:

1. **Induced seafloor deformations**
2. **Induced stresses**
3. **Fault activation risks**

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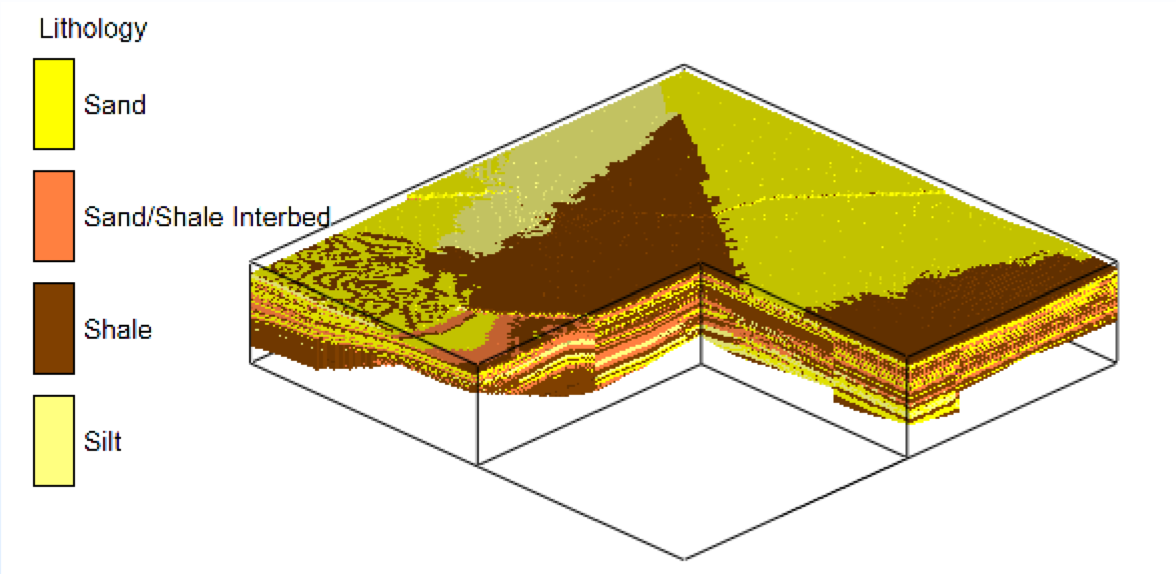
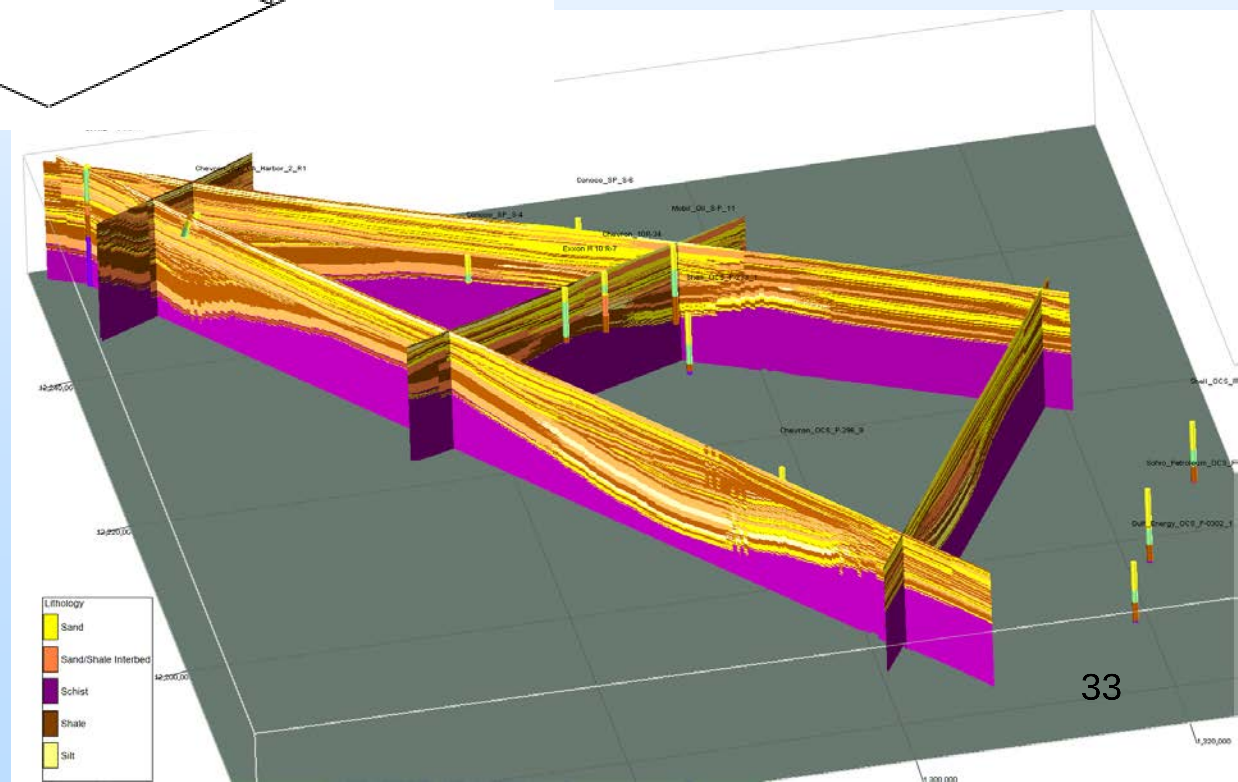
Geologic Model of Wilmington-Graben



(Top Left) Lithology Model with cut-away view . (Bottom Right) Fence-Diagram.



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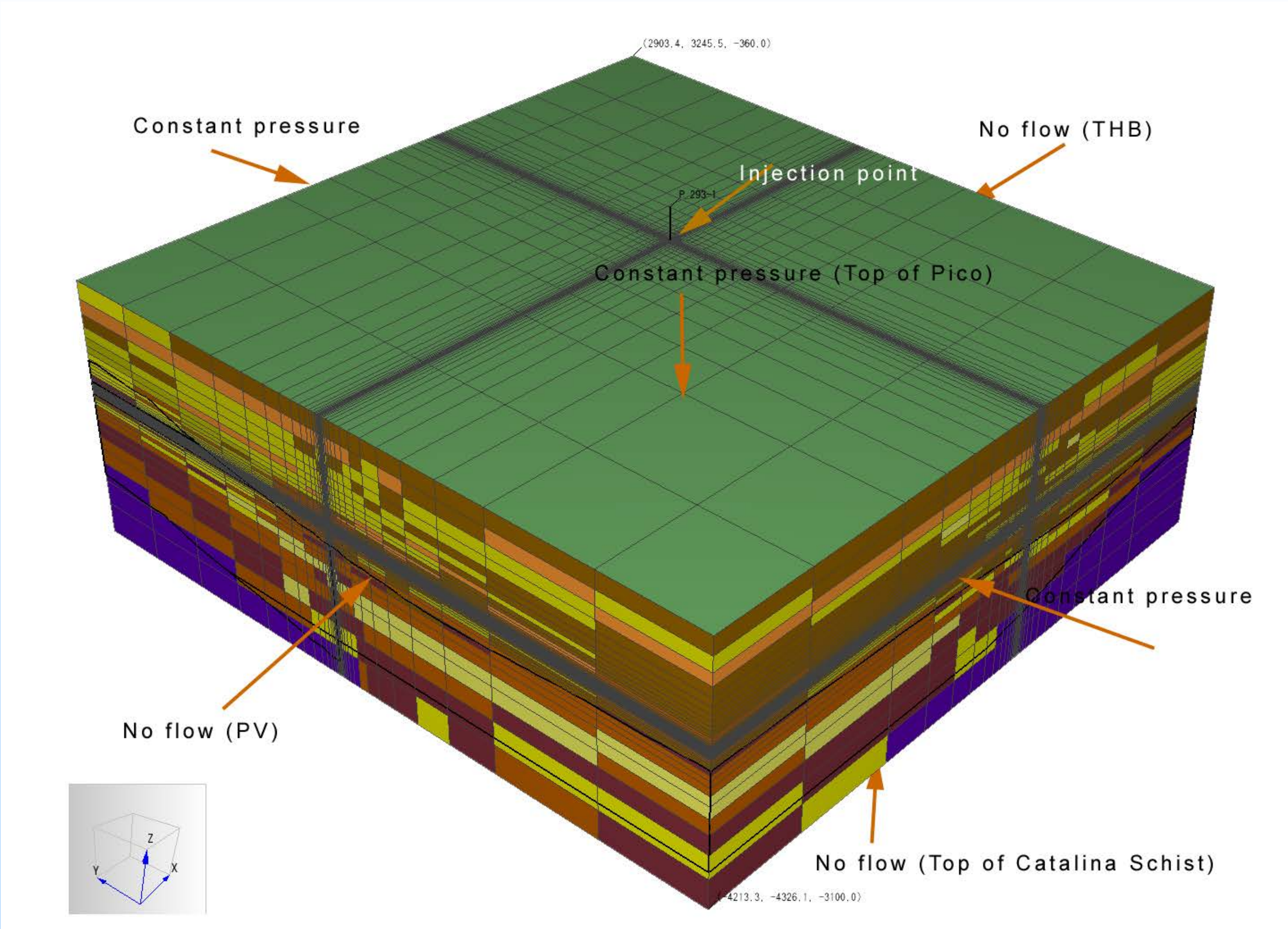
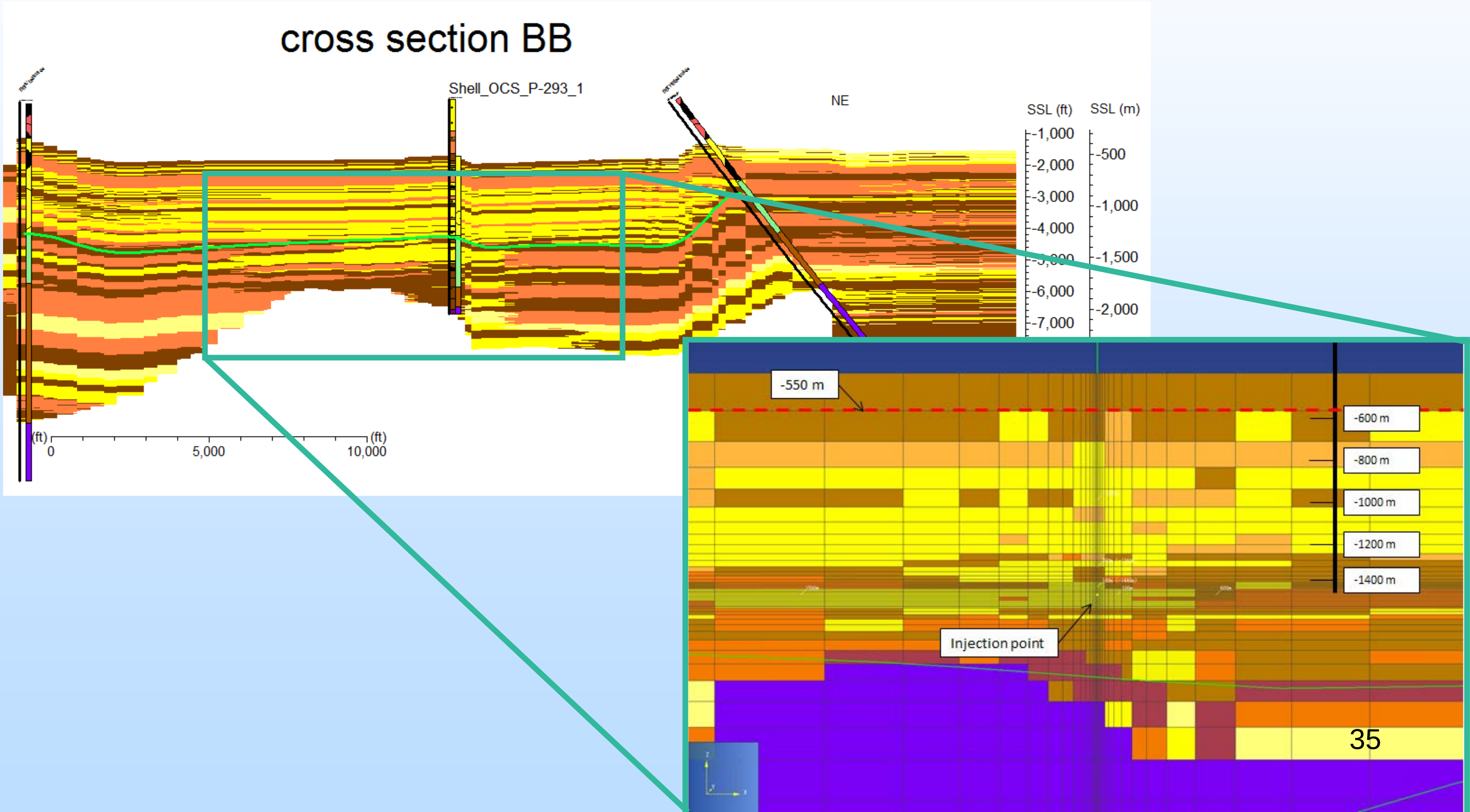
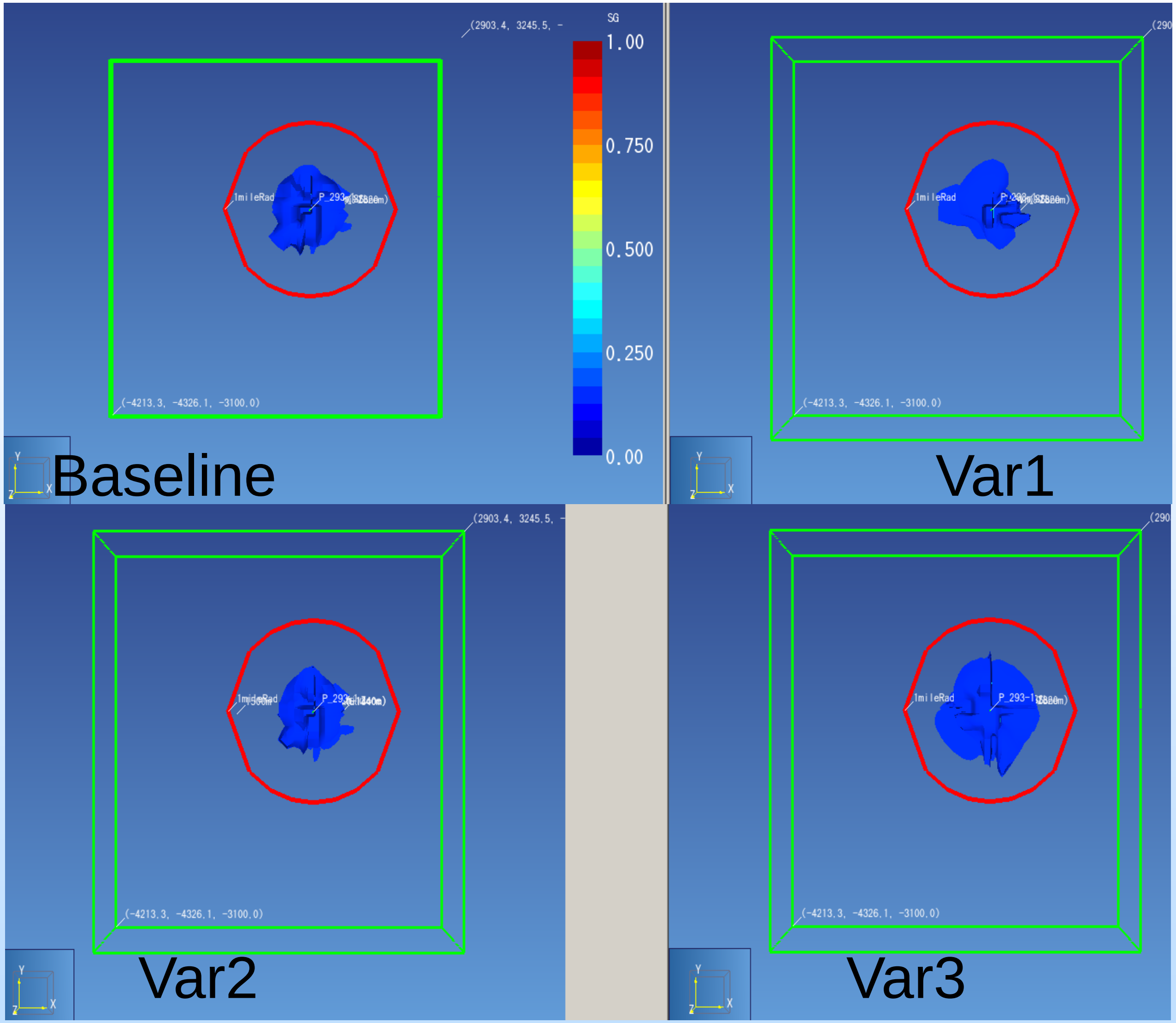
Conceptual Fluid Flow Model mid Graben area



Mapping of lithology from RW to Tough2



Gas saturation after 30 years – top view plume extent



→ Containment in 1 mile radius (red circle)

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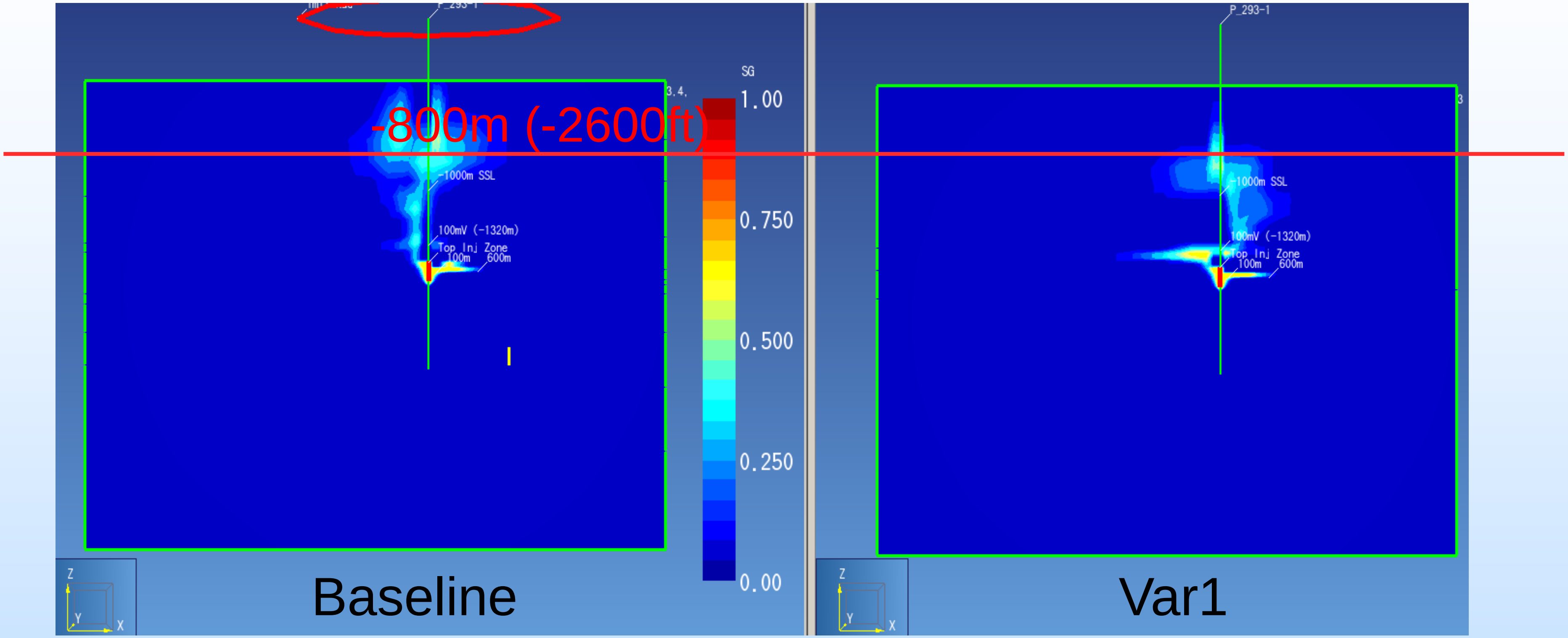
Gas saturation after 30 years –SW-NE cross section



→ (Var 1) Assuming more shale than anticipated does not ensure containment.

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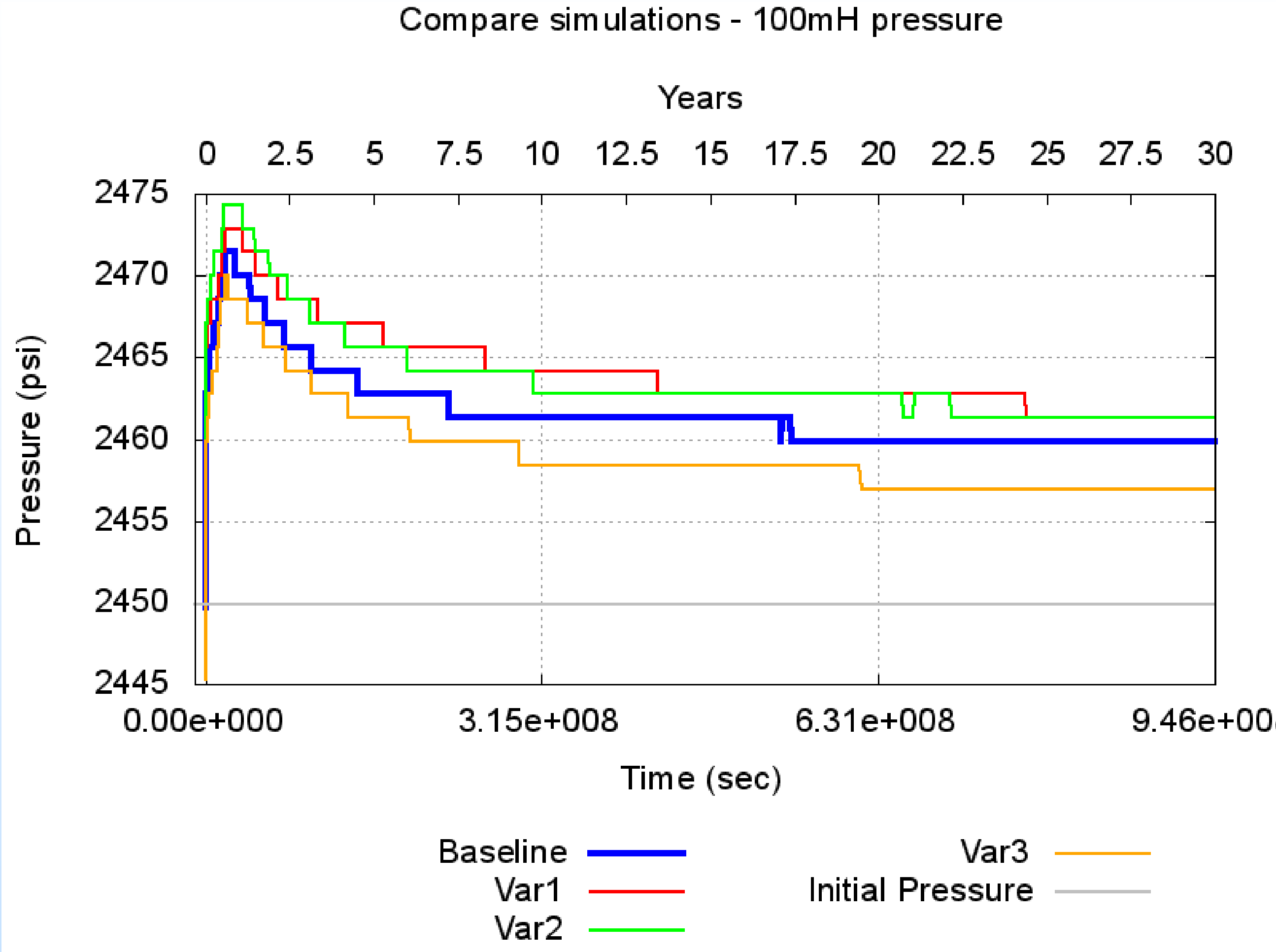
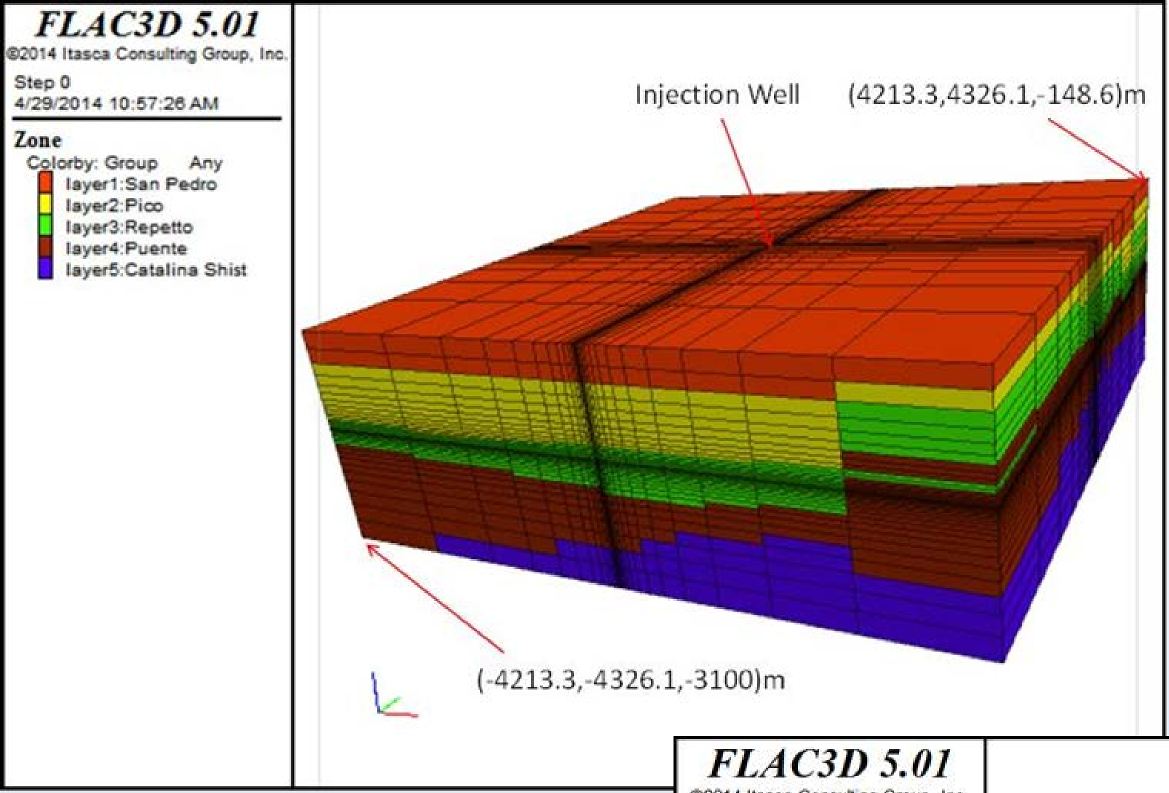
Comparing pressure at different monitoring points



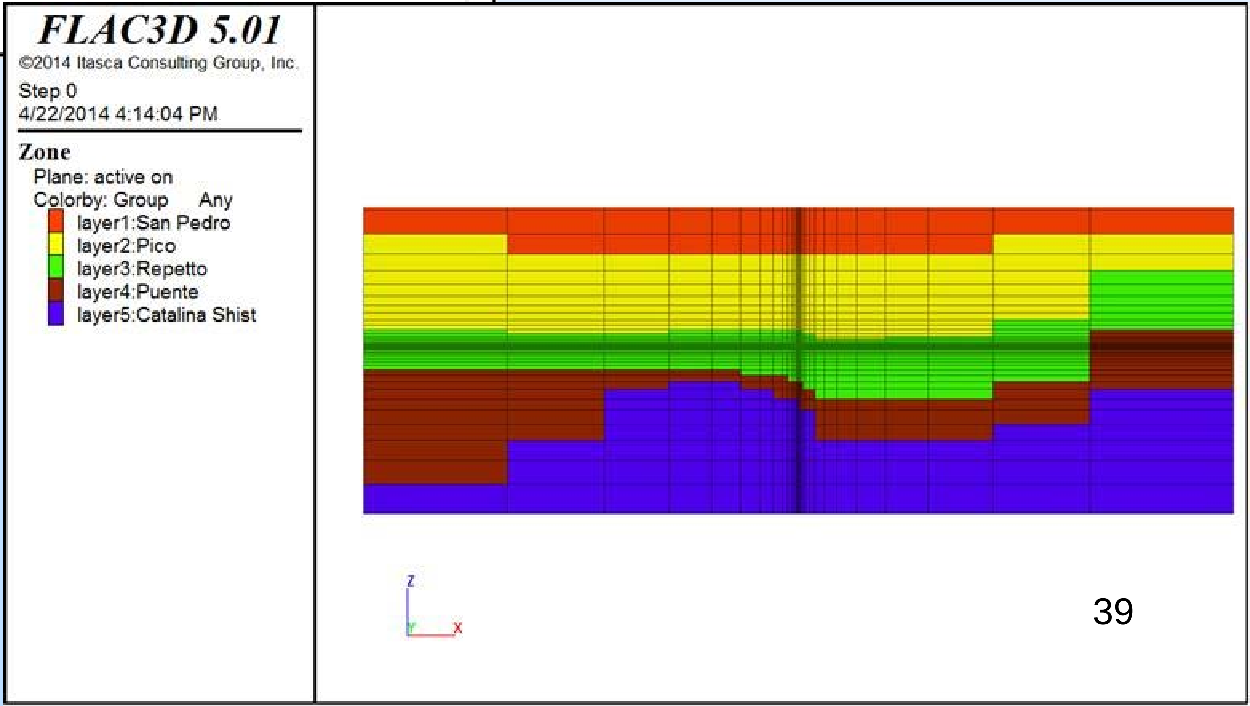
ΔP 100m away from injection about 1.0% (25PSI)

	Baseline	Var1	Var2	Var3
Interbed lithology type	sand/shale	shale		
shale z permeability (mD)	6/4		6x10-4/4x10-4	
# of cells	60,690			78,540

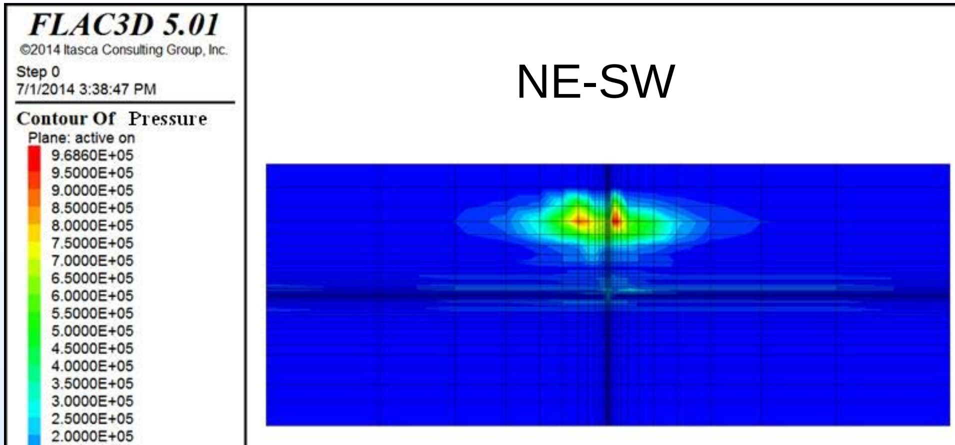
Geomechanical Modeling for Central Graben



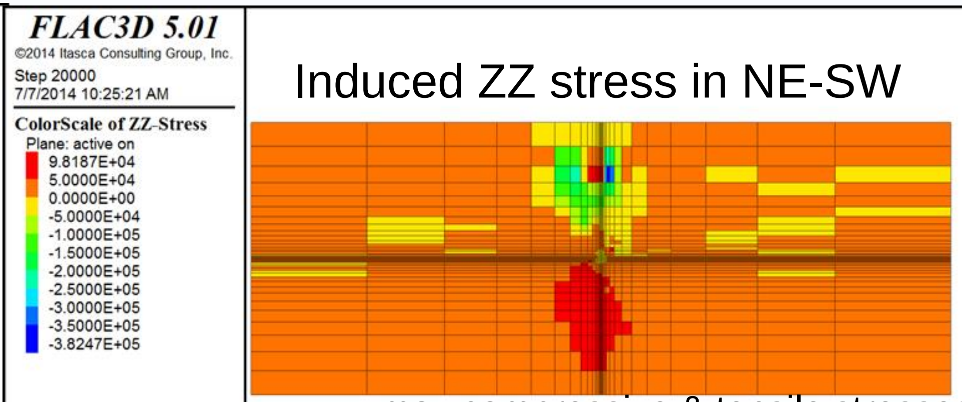
Dimension:
~ 28000ft in x & y direction
9678ft in z-direction
Total: 35,100 elements



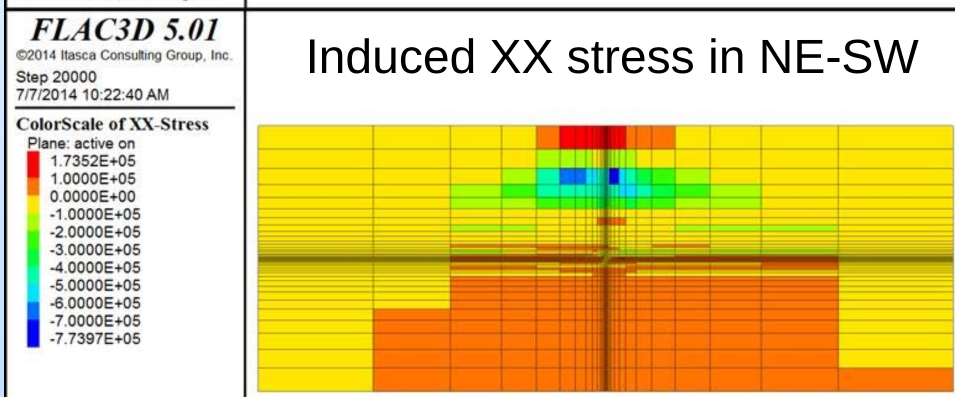
3D-Geomechanical Results, 30 years inj. – baseline model



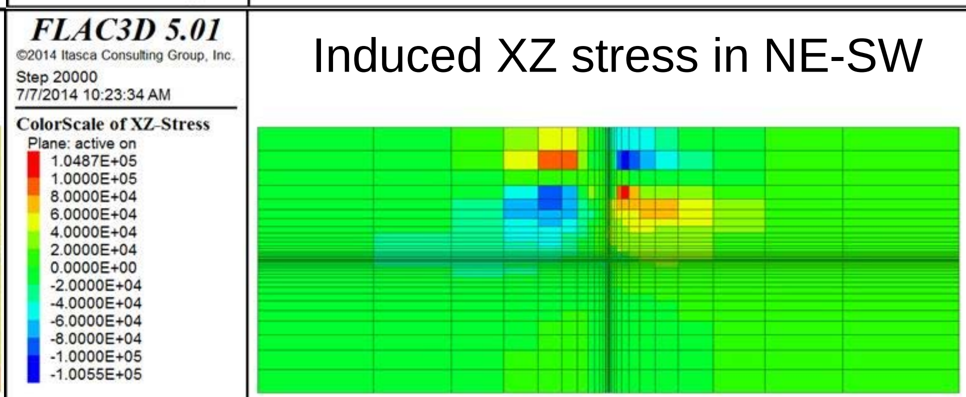
highest pressure above the injection interval, max magnitude of 9.7E5 Pa



max compressive & tensile stresses above & below injection point -- 3.8E5 Pa and 9.8E4 Pa



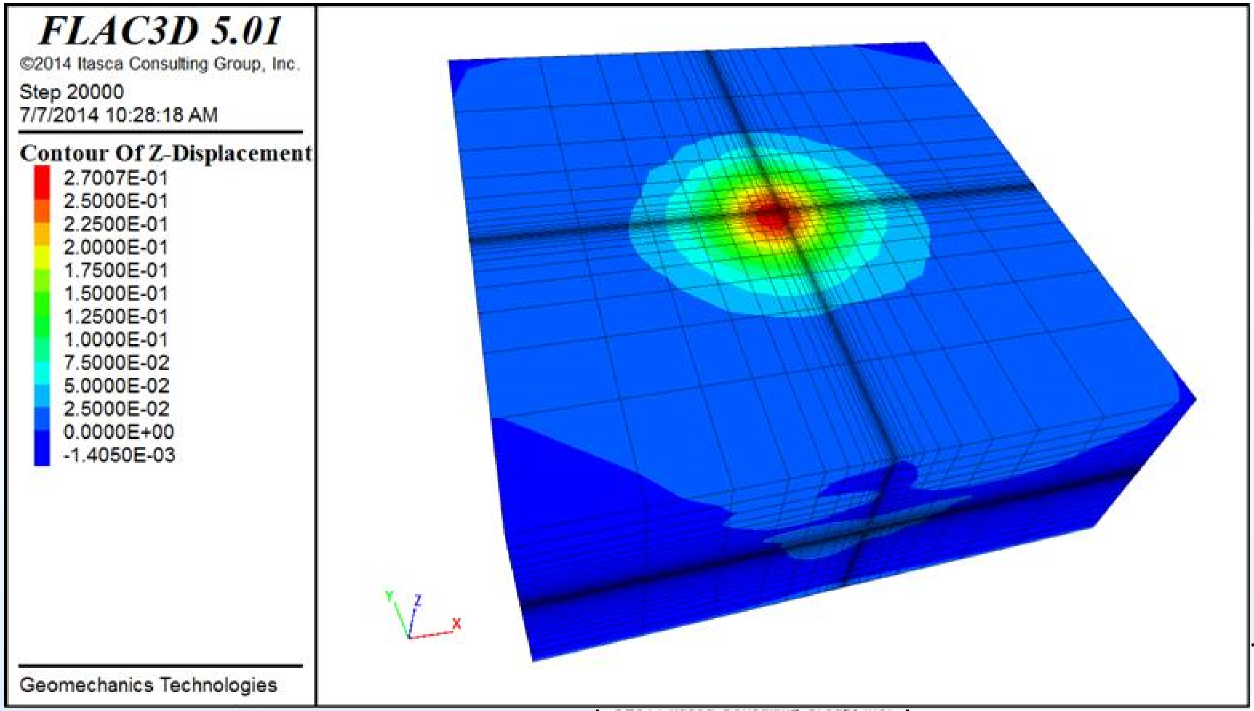
max compressive stress 7.7E5 Pa, max tensile stress 1.7E5 Pa above & below pressure concentration area

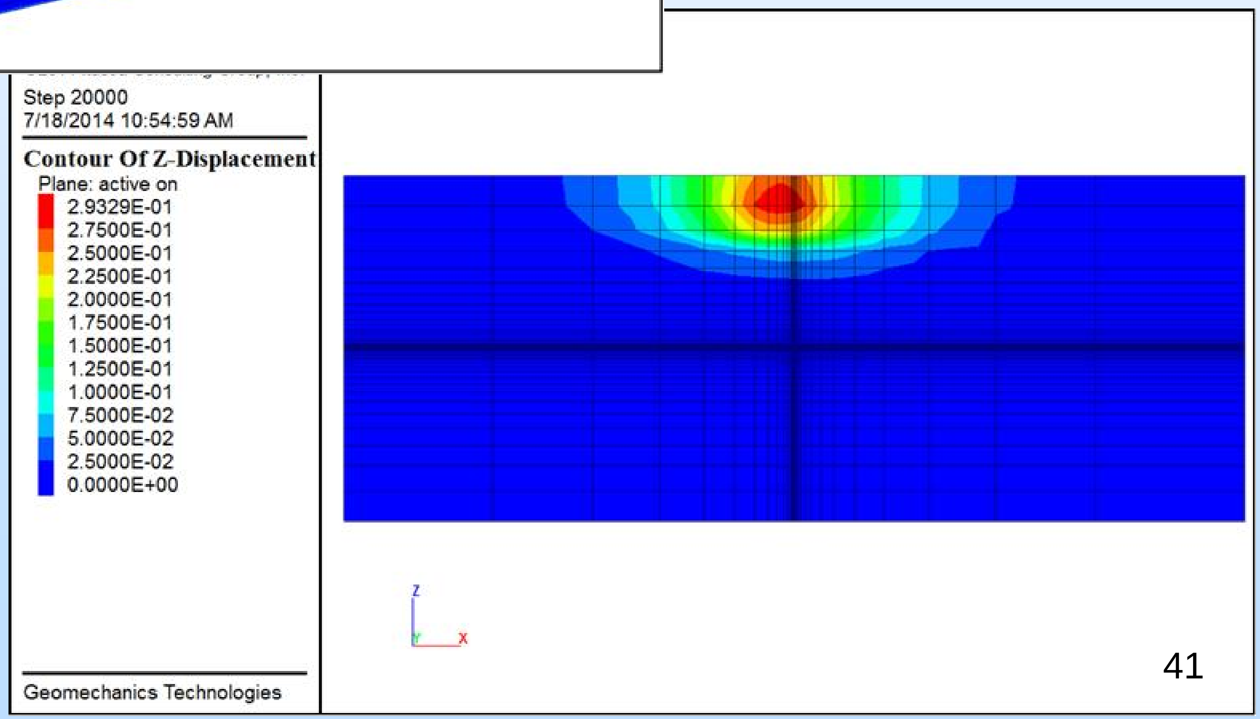


max shear stresses 1.0E5 Pa

Induced vertical displacement (meter) isometric view & view through the injection well in NE-SW direction

- Baseline model





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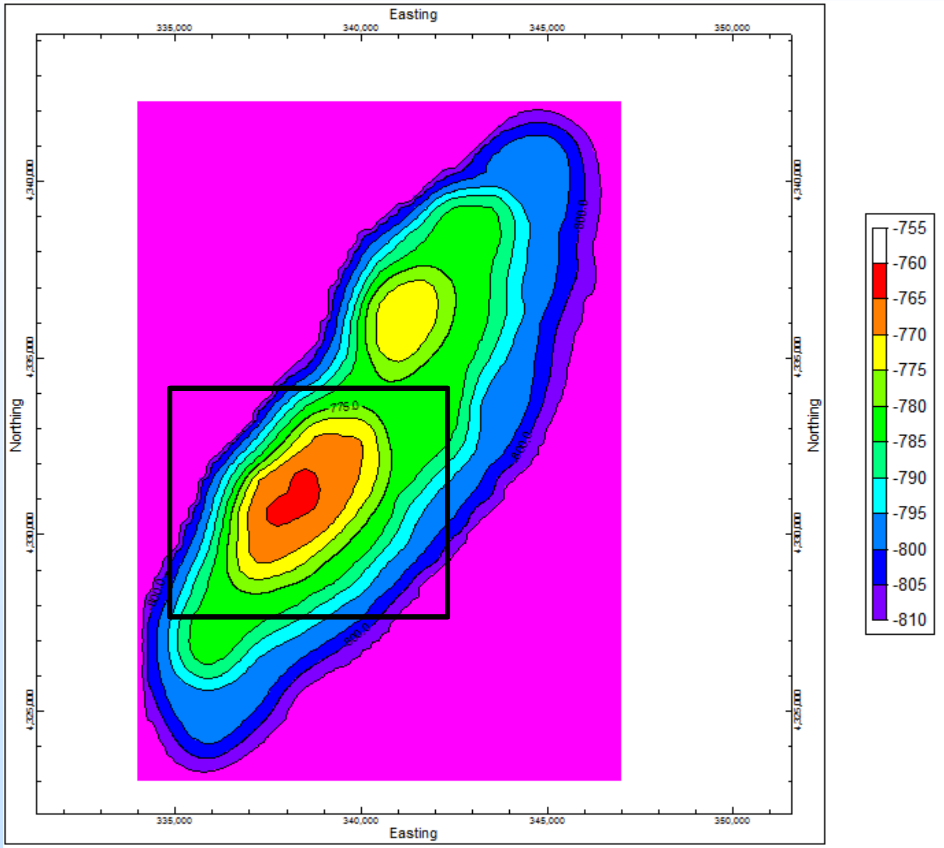
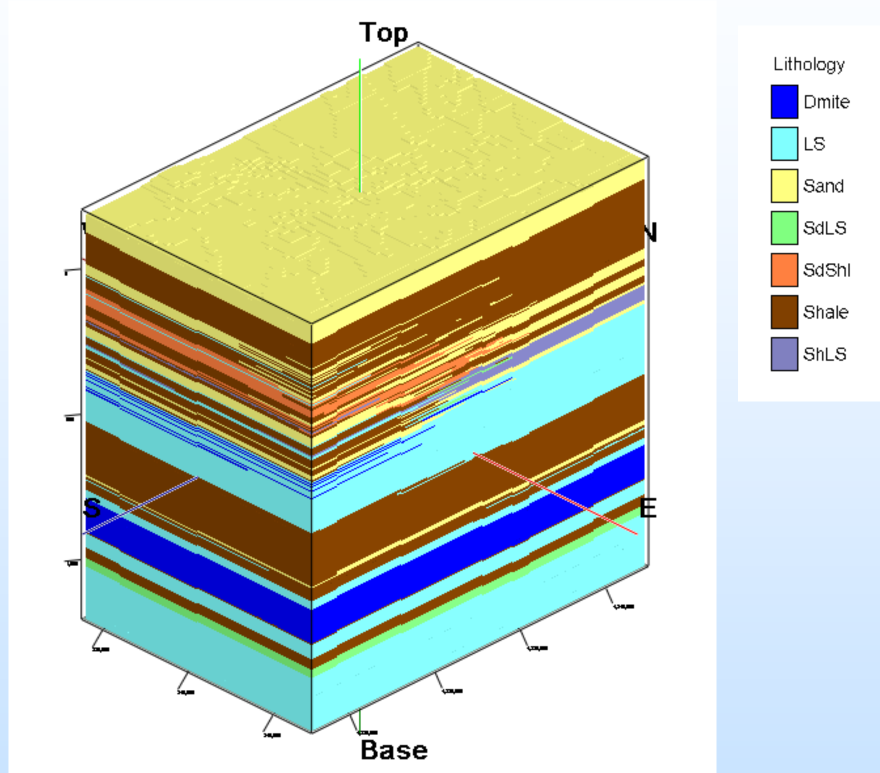
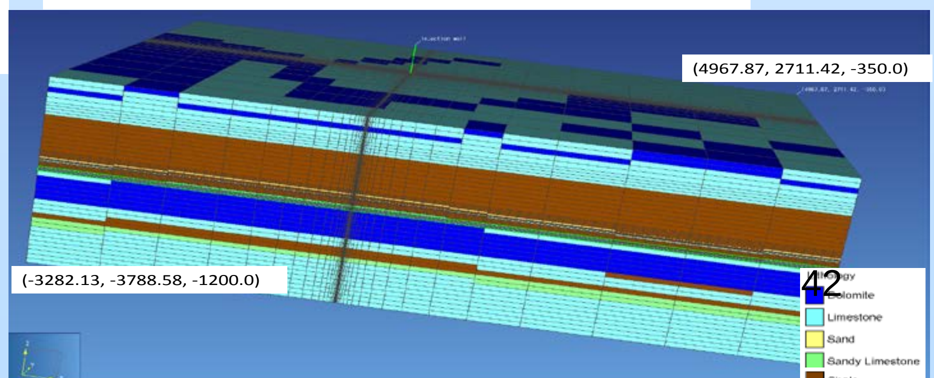
3D Fluid Flow Model for Loudon Field



Structure map of Grand Tower formation (ft-ss). Black box indicates numerical models boundary of ~8.5km x 6.5km





Quantitative Risk and Decision Analysis Tool for Caprock Integrity (QRDAT)

CO2 injection Risk Analysis Tool Wilmington Graben

MECHANICAL STATE

	tens frac		fault reac		well fail	
1. STRESS						
Max P/min princ stress						
a. ≥ 0,75	0	100	0	100	0	100
b. 0,5-0,75	1	10	1	10	1	10
c. ≤ 0,5	0	1	0	1	0	1
Stress regime						
a. Compressional	1	100	1	100	1	100
b. Transform	0	10	0	10	0	10
c. Extensional	0	1	0	1	0	1
Shmin/Sv						
a. < 0.55	0	1	0	100	0	100
b. 0.55-0.65	0	1	0	10	0	10
c. > 0.65	1	1	1	1	1	1
2. PRESSURE						
Desired Max P/Discovery P						
a. ≥ 1.5	0	100	0	100	0	100
b. 1.25-1.5	0	10	0	10	0	10
c. ≤ 1.25	1	1	1	1	1	1
Max P/formation depth						
a. ≥ 0.75	0	100	0	100	0	100
b. 0.625-0.75	0	10	0	10	0	10
c. ≤ 0.625	1	1	1	1	1	1
3. FAULTS						
Fault boundaries						
a. Multiple bounding faults	1	1	1	100	1	100
b. One bounding fault	0	1	0	10	0	10
c. None	0	1	0	1	0	1
Natural seismicity						
a. High	1	100	1	100	1	100
b. Moderate	0	10	0	10	0	10
c. Low	0	1	0	1	0	1
Category Score	214		313		313	
Category Total Score	840	*1902*				
TOTAL SCORE	1839	*4314*				

CAPROCK-STORAGE ZONE SYSTEM

	tens frac		fault reac		well fail	
4. STORAGE ZONE SPECIFIC						
Lateral extent/storage zone depth						
a. <25	1	100	1	100	1	100
b. 25-100	0	10	0	10	0	10
c. >100	0	1	0	1	0	1
Storage zone thickness/storage zone depth						
a. > 0.5	0	100	0	100	0	1
b. 0.1-0.5	0	10	0	10	0	1
c. < 0.1	1	1	1	1	1	1
5. CAPROCK SPECIFIC						
Caprock heterogeneity						
a. Significant	1	100	1	100	1	1
b. Moderate	0	10	0	10	0	1
c. Low	0	1	0	1	0	1
Caprock strength						
a. Weak	0	100	0	100	0	100
b. Moderate	1	10	1	10	1	10
c. Strong	0	1	0	1	0	1
Caprock thickness						
a. ≤ 3m	0	100	0	100	0	1
b. 3-30 m	1	10	1	10	1	1
c. ≥ 30 m	0	1	0	1	0	1
Caprock lateral extent/caprock thickness						
a. <25	1	100	1	100	1	100
b. 25-100	0	10	0	10	0	10
c. >100	0	1	0	1	0	1
Caprock permeability						
a. k > 1E-15 m2	0	100	0	1	0	1
b. 1E-18 m2 ≤ k ≤ 1E-15 m2	1	10	1	1	1	1
c. k < 1E-18 m2	0	1	0	1	0	1
Number of caprocks						
a. Single	0	100	0	100	0	100
b. Double	0	10	0	10	0	10
c. Multiple	1	1	1	1	1	1
Caprock dip						
a. γ ≥ 8°	1	1	1	100	1	1
b. 2°≤γ≤8°	0	1	0	10	0	1
c. γ ≤ 2°	0	1	0	1	0	1
Category Score	333		423		216	
Category Total Score	972	*2007*				

OPERATIONS

	tens frac		fault reac		well fail	
6. OPERATIONS						
Well density						
a. > 15 km-2	0	1	0	1	0	100
b. 5-15 km-2	0	1	0	1	0	10
c. < 5 km-2	1	1	1	1	1	1
No. of uncased wells/total no. of wells						
a. > 0.6	0	1	0	1	0	100
b. 0.2-0.6	0	1	0	1	0	10
c. < 0.2	1	1	1	1	1	1
ΔT between CO2 and storage zone						
a. ≥ 60 ◦C	0	100	0	100	0	1
b. 30 ◦C - 60 ◦C	1	10	1	10	1	1
c. ≤ 30 ◦C	0	1	0	1	0	1
Category Score	12		12		3	
Category Total Score	27	*405*				

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CO2 injection Risk Analysis Tool Wilmington Graben

MECHANICAL STATE	tens frac		fault reac		well fail	
1. STRESS						
Max P/min princ stress						
a. ≥ 0,75	0	100	0	100	0	100
b. 0,5-0,75	1	10	1	10	1	10
c. ≤ 0,5	0	1	0	1	0	1
Stress regime						
a. Compressional	1	100	1	100	1	100
b. Transform	0	10	0	10	0	10
c. Extensional	0	1	0	1	0	1
Shmin/Sv						
a. < 0.55	0	1	0	100	0	100
b. 0.55-0.65	0	1	0	10	0	10
c. > 0.65	1	1	1	1	1	1
2. PRESSURE						
Desired Max P/Discovery P						
a. ≥ 1.5	0	100	0	100	0	100
b. 1.25-1.5	0	10	0	10	0	10
c. ≤ 1.25	1	1	1	1	1	1
Max P/formation depth						
a. ≥ 0.75	0	100	0	100	0	100
b. 0.625-0.75	0	10	0	10	0	10
c. ≤ 0.625	1	1	1	1	1	1
3. FAULTS						
Fault boundaries						
a. Multiple bounding faults	1	1	1	100	1	100
b. One bounding fault	0	1	0	10	0	10
c. None	0	1	0	1	0	1
Natural seismicity						
a. High	1	100	1	100	1	100
b. Moderate	0	10	0	10	0	10
c. Low	0	1	0	1	0	1

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CAPROCK-STORAGE ZONE SYSTEM

	tens frac		fault reac		well fail	
4. STORAGE ZONE SPECIFIC						
Lateral extent/storage zone depth						
a. <25	1	100	1	100	1	100
b. 25-100	0	10	0	10	0	10
c. >100	0	1	0	1	0	1
Storage zone thickness/storage zone depth						
a. > 0.5	0	100	0	100	0	1
b. 0.1-0.5	0	10	0	10	0	1
c. < 0.1	1	1	1	1	1	1
5. CAPROCK SPECIFIC						
Caprock heterogeneity						
a. Significant	1	100	1	100	1	1
b. Moderate	0	10	0	10	0	1
c. Low	0	1	0	1	0	1
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a. Weak	0	100	0	100	0	100
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c. Strong	0	1	0	1	0	1
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a. ≤ 3m	0	100	0	100	0	1
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Caprock lateral extent/caprock thickness						
a. <25	1	100	1	100	1	100
b. 25-100	0	10	0	10	0	10
c. >100	0	1	0	1	0	1
Caprock permeability						
a. k > 1E-15 m2	0	100	0	1	0	1
b. 1E-18 m2 ≤ k ≤ 1E-15 m2	1	10	1	1	1	1
c. k < 1E-18 m2	0	1	0	1	0	1
Number of caprocks						
a. Single	0	100	0	100	0	100
b. Double	0	10	0	10	0	10
c. Multiple	1	1	1	1	1	1
Caprock dip						
a. $\gamma \geq 8°$	1	1	1	100	1	1
b. $2° \leq \gamma \leq 8°$	0	1	0	10	0	1
c. $\gamma \leq 2°$	0	1	0	1	0	1

Absolute risk scores for the different example cases

Category	Range of risk scores	Kevin Dome	Loudon	Wilmington Graben	Sleipner	In Salah
Mechanical state	21-1902	345	660	840	102	390
Caprock-Storage Zone system	27-2007	27	45	972	342	27
Operations	9-405	9	27	27	9	27
TOTAL	57-4314	381	732	1839	453	444

The relative risk ranking based on three types of risk factors

Category	Range of risk scores	Kevin Dome	Loudon	Wilmington Graben	Sleipner	In Salah
Tensile fracturing	19-1405	127	235	559	154	145
Fault (re)activation	19-1603	127	244	748	154	154
Wellbore failure	19-1306	127	253	532	145	145
TOTAL	57-4314	381	732	1839	453	444

The relative risk ranking based on failure type

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Relative Risk Comparison

Number of times that a high, moderate or low risk is assigned to the different cases

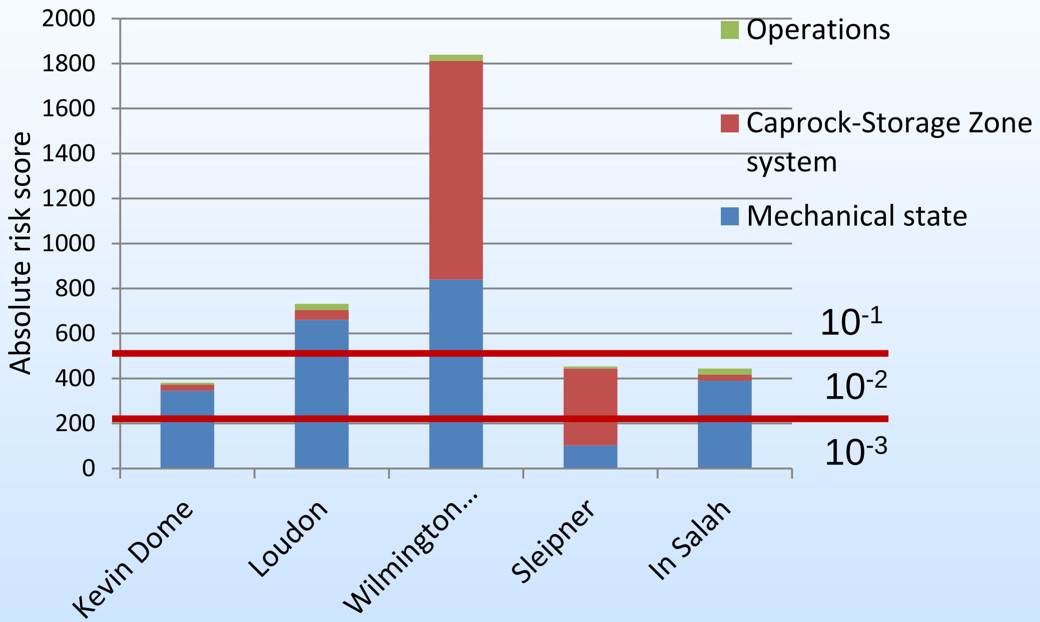

Table 3. Relative Risk Scores and Order-of Magnitude Probabilities

Relative Ranking Score Value	Loss Event Probability Order-of-Magnitude Value
greater than 500	10^{-1}
301 – 500	10^{-2}
201 – 300	10^{-3}
101 – 200	10^{-4}
Less than 100	10^{-5}

Main observations:

- Mechanical state (pressure & stresses) contributes most to failure risk in most cases.
- For the Wilmington Graben, the caprock-reservoir system is highly unfavorable.
- State of operations contribute relatively small amount to leakage risk.
- Sleipner and In Salah show approximately equal leakage risk, but this is caused by different types of risks.

Recommendations and Guidelines for Caprock Characterization and CO_2 Injection Operating Practices

The set of risk factors can be divided into three main groups:

- mechanical state of the storage system, which includes stresses, pressure and faults;
- caprock-storage zone system, including reservoir- and caprock geometry and properties; and
- operations, which includes the status of the wells and injection practices.

All of the risk factors may increase or decrease the risk of caprock integrity loss in three ways:

- tensile failure of the caprock, creating potential flow paths in initially unfractured caprock;
- fault (re-)activation, potentially opening fault planes as flow paths; and
- wellbore failure, previously drilled wellbores, insufficiently plugged and abandoned, may act as vertical fluid conduits.

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Recommendations and Guidelines for Caprock Characterization and CO_2 Injection Operating Practices

Recommendations for Characterization Efforts

- Logging
- 3D Seismic
- Geomechanical analysis (well testing)
- Core analysis

Recommendations for Siting Criteria

- Surface conditions
- Existing well density and conditions
- Geologic conditions (depth, porosity, perm, caprock, faulting)
- Geomechanical conditions (stress, properties)

Recommendations for Operating Practices

- Well design and placement
- Pressure and rate limits per well

Recommendations for Monitoring (based on site and planned ops)

Summary

1. Risks for gas leakage events are generally higher than previously estimated and published. 10^{-1} to 10^{-2} , not 10^{-4}
   - Based on historical observations
   - Based on current risk analysis approach
2. Leakage out of zone, however, does not imply leakage to the surface and is generally manageable
3. Analytical solutions developed and available to estimate induced shear stresses to first order
4. Integrated Geology-Geomechanics-Fluid flow modeling approach developed and recommended for risk analysis
5. Risk Analysis Tool Developed and Applied to Several Sample Storage Projects

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Accomplishments and Project Status:

- Completed Historical Data Review & Documentation of Caprock Integrity in both U.S. and European Gas Storage Industry
- Completed Analytical Description and Comparison of Numerical Simulations Describing Caprock Stresses Induced by CO2 Injection
- Completing 3D Geologic Models, Fluid Flow Models, and Geomechanical Models for Three Sample Fields (Wilmington-Graben, Kevin Dome, Louden).
- Developed Risk Analysis Tool for Caprock Integrity (geomechanical factors) and Demonstrated on 5 Sample Projects
- Completing Recommendations and Guidelines for Caprock Characterization and CO_2 Injection Operating Practices
- Final Reporting and Documentation.

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Appendix

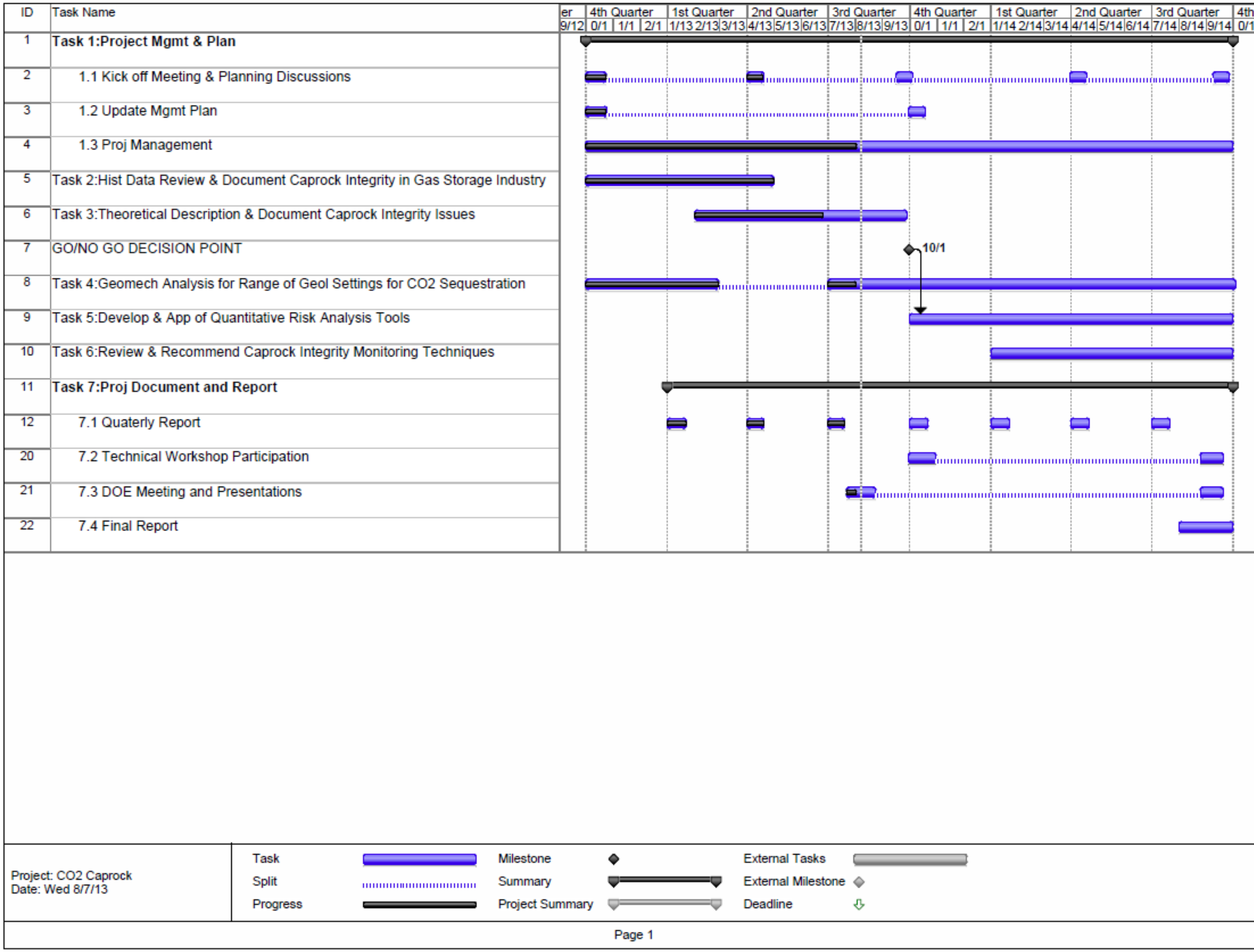
– These slides will not be discussed during the presentation, but are mandatory

GeoMechanics Technologies

Team Members

- Principal Investigator
  - Dr. Mike Bruno
- Project Manager & Sr. Engineer
  - Kang Lao
- Sr Research Engineer
  - Julia Diessl
- Research Engineer
  - Jing Xiang
  - Ellen van der Veer
- Sr. Research Geologist
  - Jean Young
- Research Geologist
  - Nicky White
  - Bill Childers

Gantt Chart



ID
Task Name
4th Quarter
1st Quarter
2nd Quarter
3rd Quarter
4th Quarter
1st Quarter
2nd Quarter
3rd Quarter
4th
1 Task 1:Project Mgmt & Plan
2 1.1 Kick off Meeting & Planning Discussions
3 1.2 Update Mgmt Plan
4 1.3 Proj Management
5 Task 2:Hist Data Review & Document Caprock Integrity in Gas Storage Industry
6 Task 3:Theoretical Description & Document Caprock Integrity Issues
7 GO/NO GO DECISION POINT
10/1
8 Task 4:Geomech Analysis for Range of Geol Settings for CO2 Sequestration
9 Task 5:Develop & App of Quantitative Risk Analysis Tools
10 Task 6:Review & Recommend Caprock Integrity Monitoring Techniques
11 Task 7:Proj Document and Report
12 7.1 Quaterly Report
20 7.2 Technical Workshop Participation
21 7.3 DOE Meeting and Presentations
22 7.4 Final Report
Project: CO2 Caprock
Date: Wed 8/7/13
Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External Milestone
Deadline
Page 1