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Development of Improved Caprock Integrity and Risk Assessment Techniques

Project Number (FE0009168)

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GeoMechanics Technologies

U.S. Department of Energy

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

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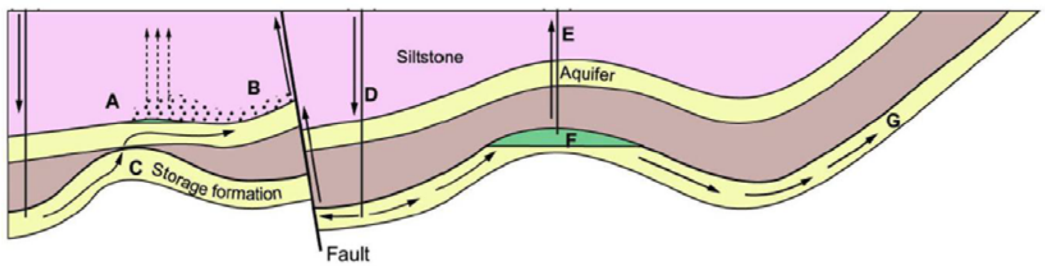
Introduction and Motivation

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

Geomechanics

- 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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Workplan

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 of 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 and control (through operating practices and limits) caprock integrity problems;
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 caprock leakage incidents, as well as to one or more large-scale injection projects that have not experienced problems; and,
6. Development and documentation of practical recommendations and guidelines for caprock characterization and operating practices to reduce caprock integrity damage risks.

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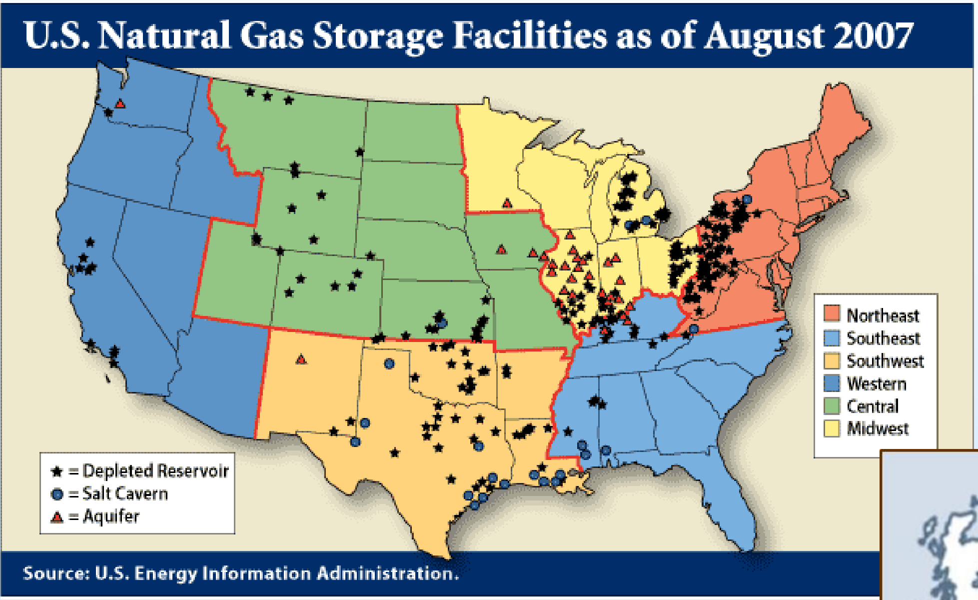
Schedule for Year 1 & Year 2

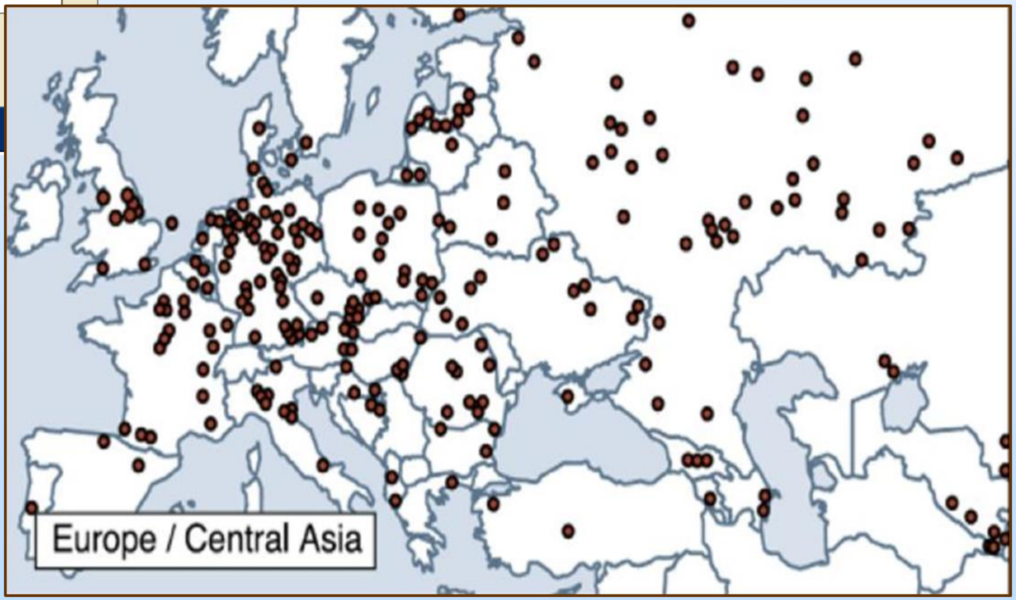
	Project Plan and Schedule															
	Period 1 (Year 1) 2013												Period 2 (Year 2) 2014			
Task Description & Milestones	1	2	3	4	5	6	7	8	9	10	11	12	Q1	Q2	Q3	Q4
Task 1. Project Mgmt & Planning																
1.1 Kickoff mtgs and planning discussions	■						■					■		■		■
1.2 Update Mgmt plan	■												■			
1.3 Project management	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Task 2. Historical data review & document caprock integrity in gas storage industry	■	■	■	■	■	■	■									
Task 3. Theoretical description & document caprock integrity issues					■	■	■	■	■	■	■	■				
Go/No Go Decision Point												◆				
Task 4. Geomechanical analysis for range of geol settings for large scale CO2 sequest	■	■	■	■	■					■	■	■	■	■	■	■
Task 5. Develop & application of quantitative risk analysis tools for caprock integrity													■	■	■	
Task 6. Review & recommend caprock integrity monitoring techniques														■	■	■
Task 7. Project Documentation and Reporting																
7.1 Quarterly Reports	■			■			■			■			■	■	■	■
7.2 Technical workshop participation										■	■					■
7.3 DOE meeting and presentations									■	■						■
7.4 Final report																■

Project Staff Members	
NAME	**TITLE**
Mike Bruno	Principal Investigator
Kang Lao	Project Manager
Jean Young	Sr Geologist
Bill Childers	Staff Geologist
Nicky White	Staff Geologist
Julia Diessl	Sr Research Engineer
Claudia Gruber	Sr Research Engineer
Jing Xiang	Research Engineer

Historical Data Review in Gas Storage Industry



IEAGHG (2009)

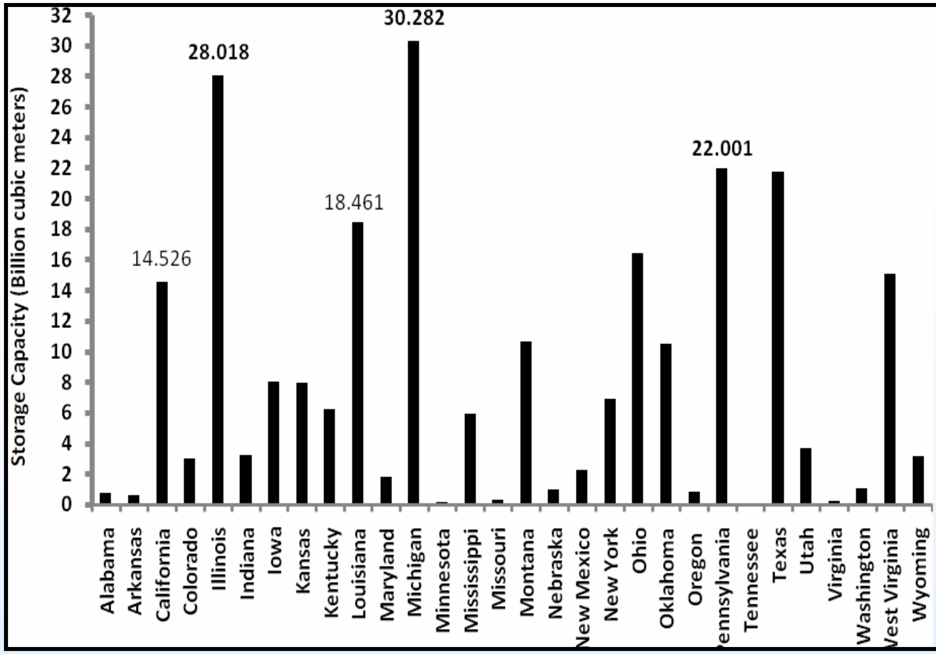


UGS sites in the Europe and Central Asia

Overview of Underground Gas Storage:

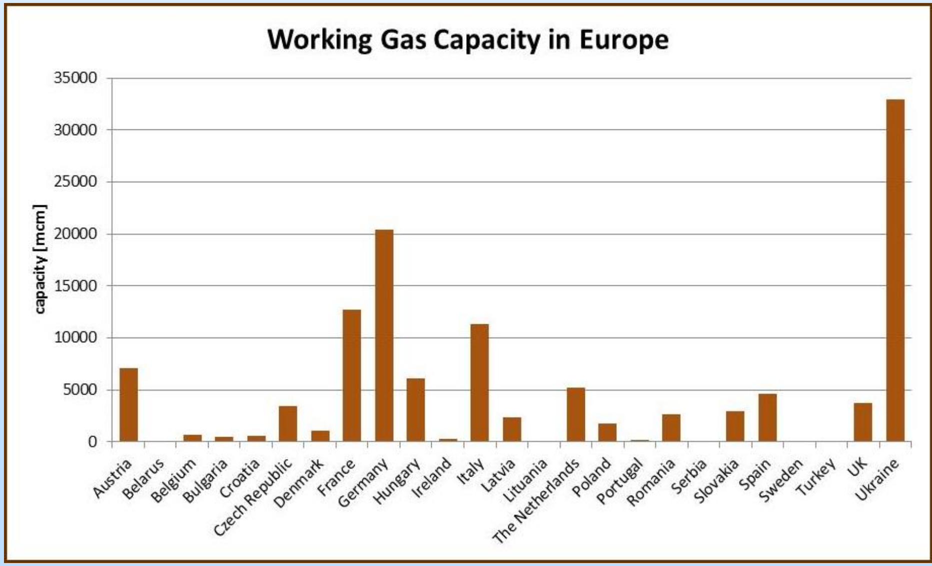
- Underground Fuel Storage (UFS) began in 1915
- As of 2005, For **U.S.** UGS:
    - 410 UGS facilities total
    - 330 in Depleted O&G Fields
    - 43 in Aquifers
    - 37 in Salt Caverns
    - < 1% in mines
- As of 2012, For **European** UGS:
    - 155 UGS facilities total
    - 82 in Depleted O&G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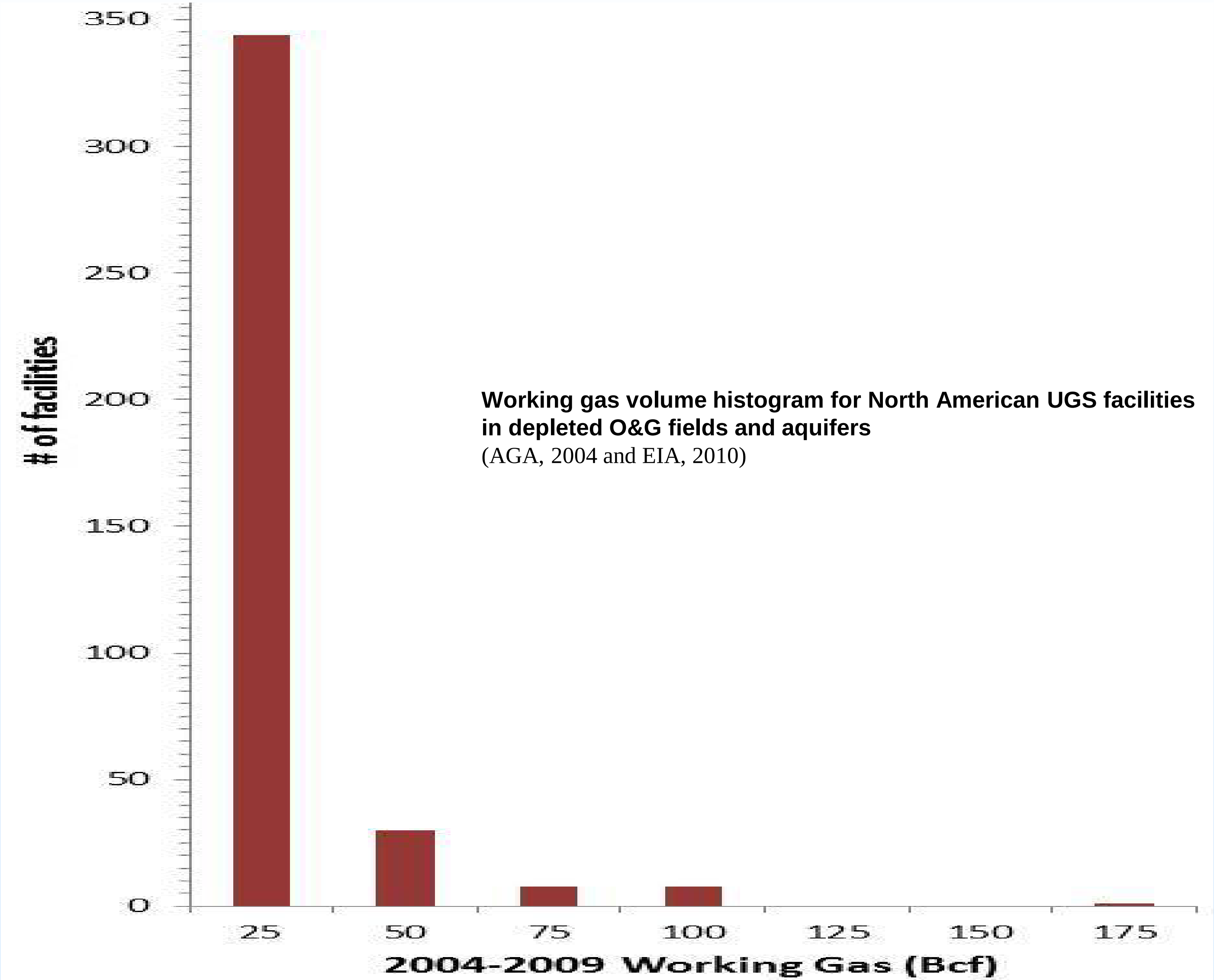

Working gas volume histogram for North American UGS facilities in depleted O&G fields and aquifers
(AGA, 2004 and EIA, 2010)

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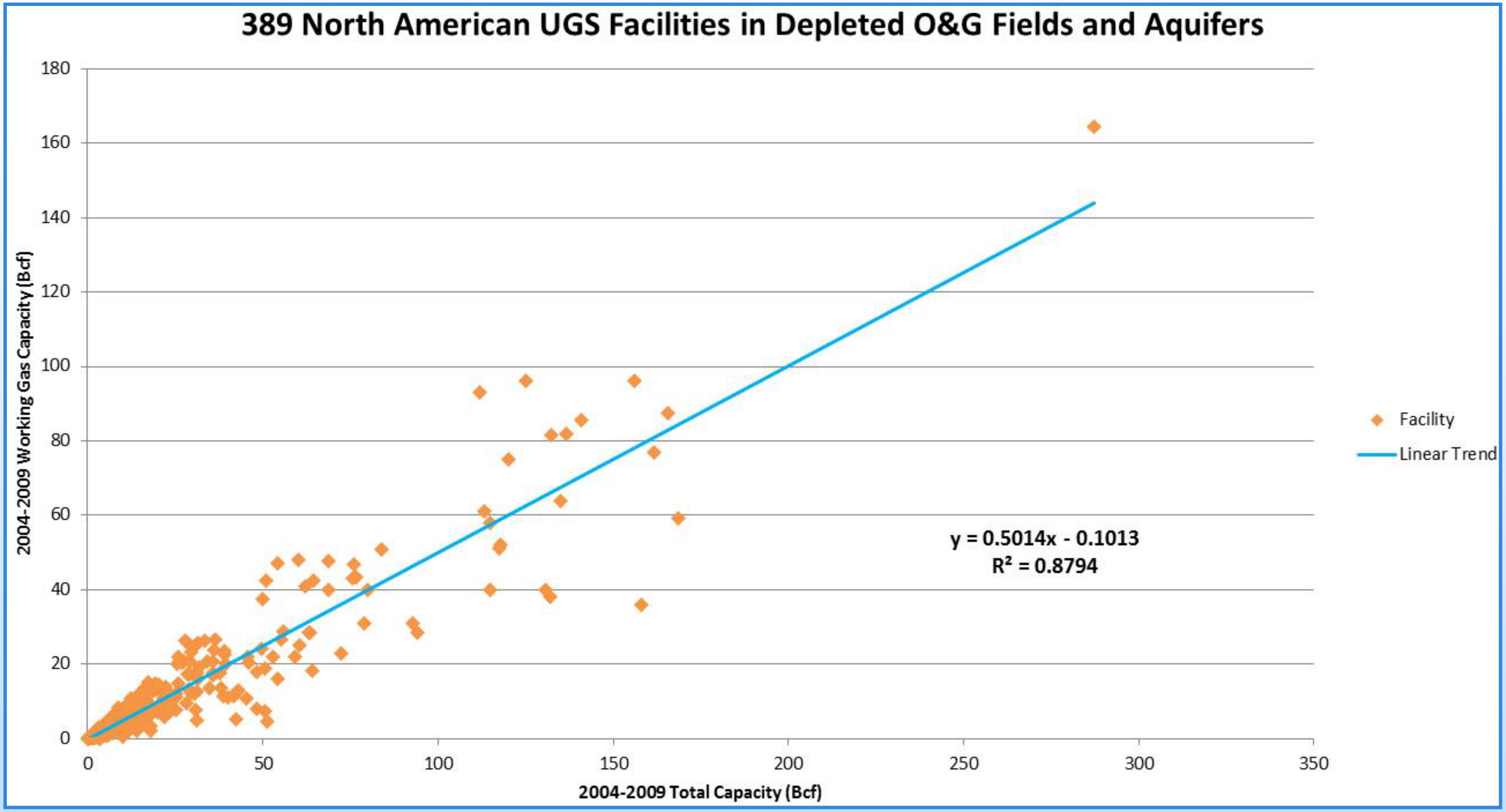

Scatterplot comparing working gas to total gas capacity for North American UGS facilities in depleted O&G fields and aquifers
(AGA, 2004 and EIA, 2010)

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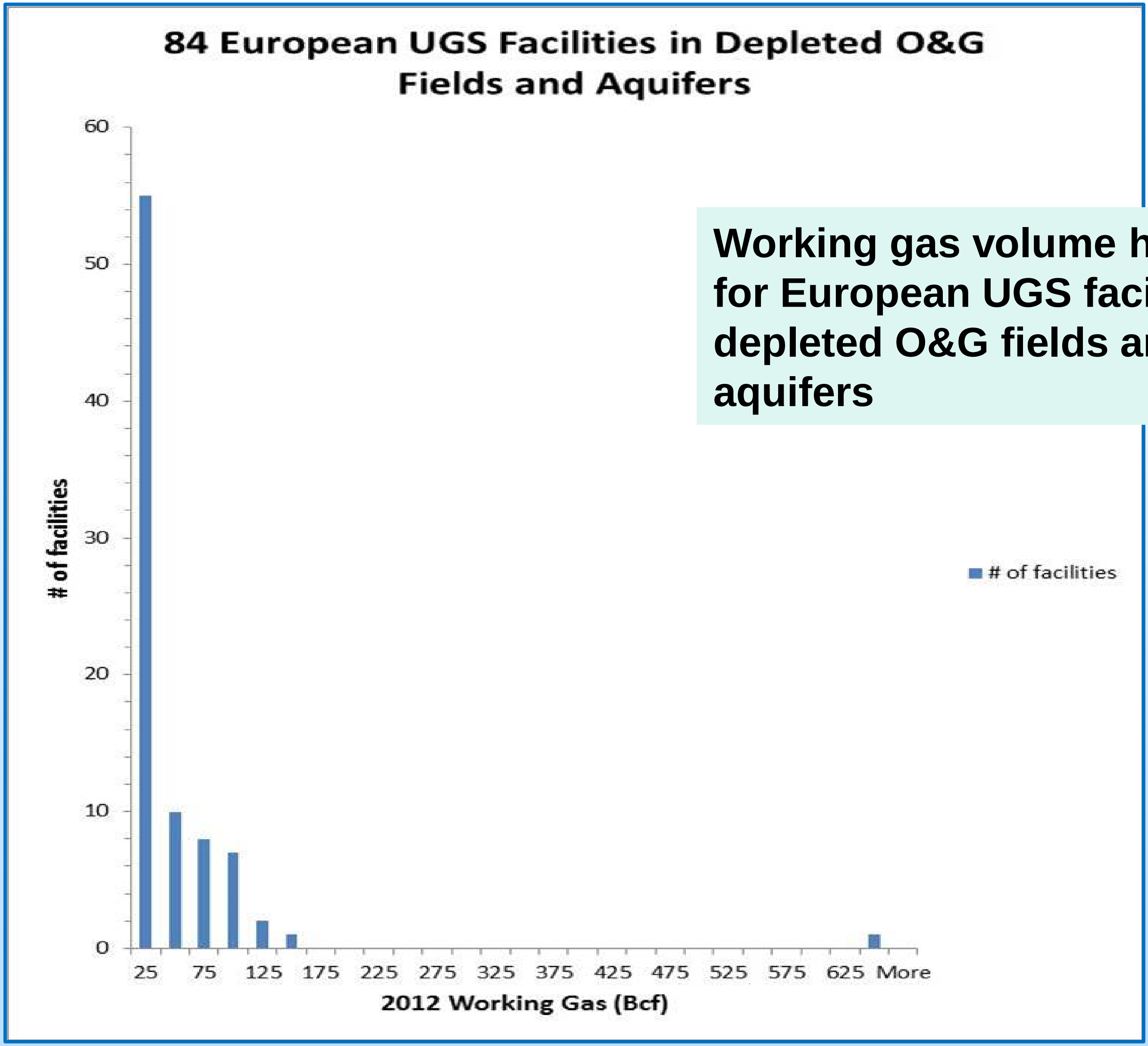
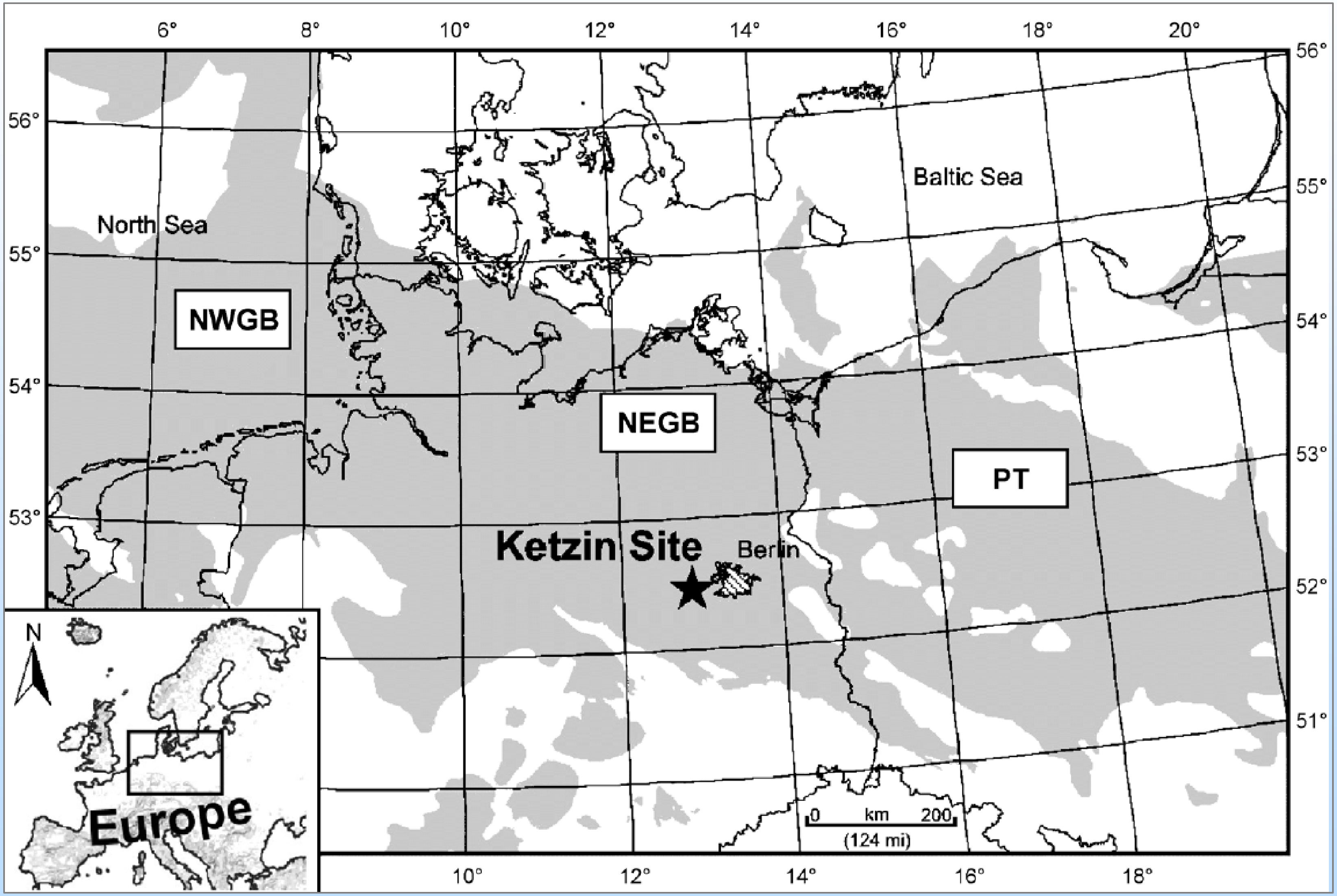
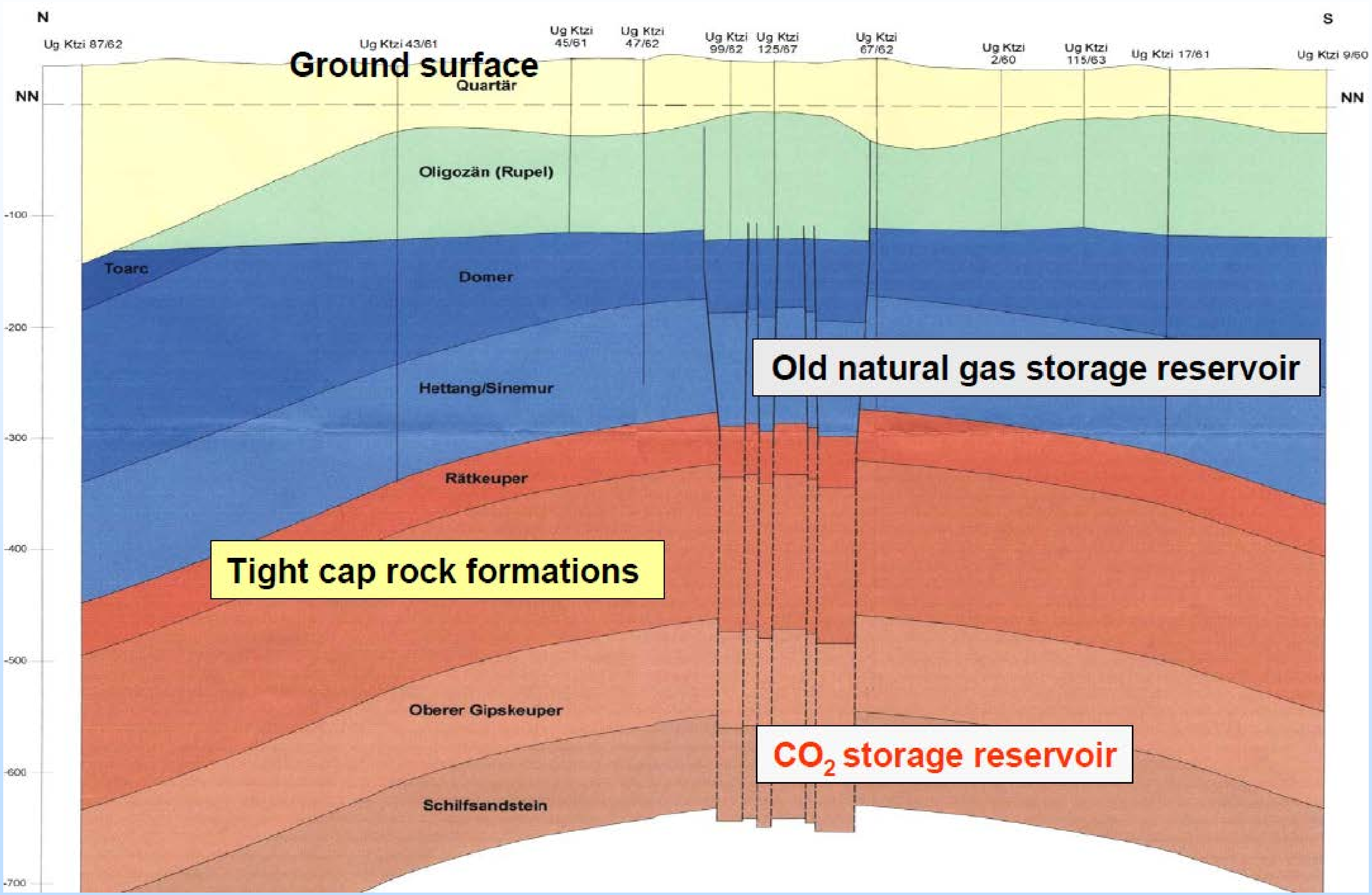


Working gas volume histogram for European UGS facilities in depleted O&G fields and aquifers

Ketzin



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



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

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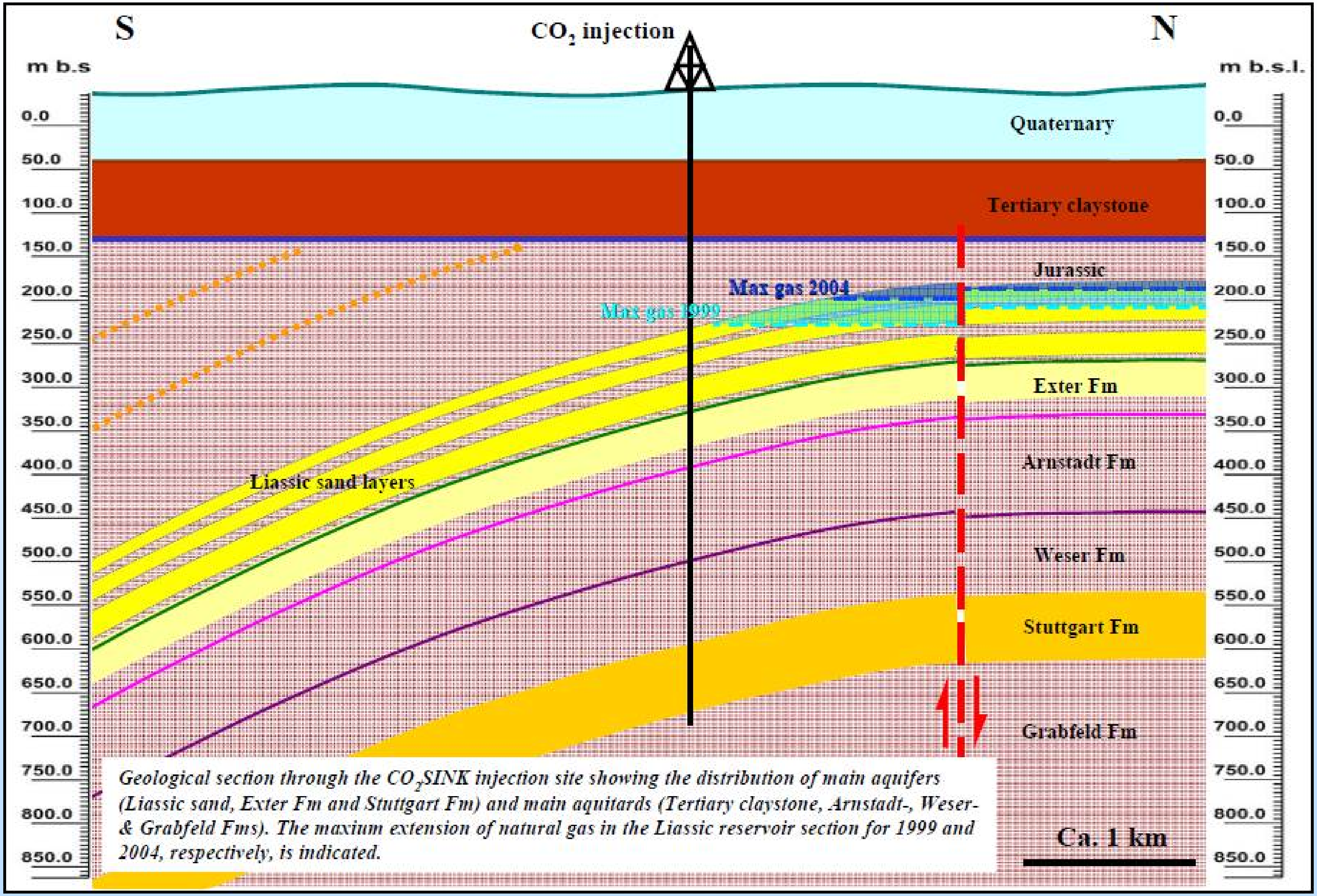

Geological section through the CO_2SINK injection site showing the distribution of main aquifers (Liassic sand, Exter Fm and Stuttgart Fm) and main aquitards (Tertiary claystone, Arnstadt-, Weser- & Grabfeld Fms). The maxium extension of natural gas in the Liassic reservoir section for 1999 and 2004, respectively, is indicated.

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)

Loudon & Illinois Basin

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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

siltstones

glacial drift

Limestones

dolomites

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.

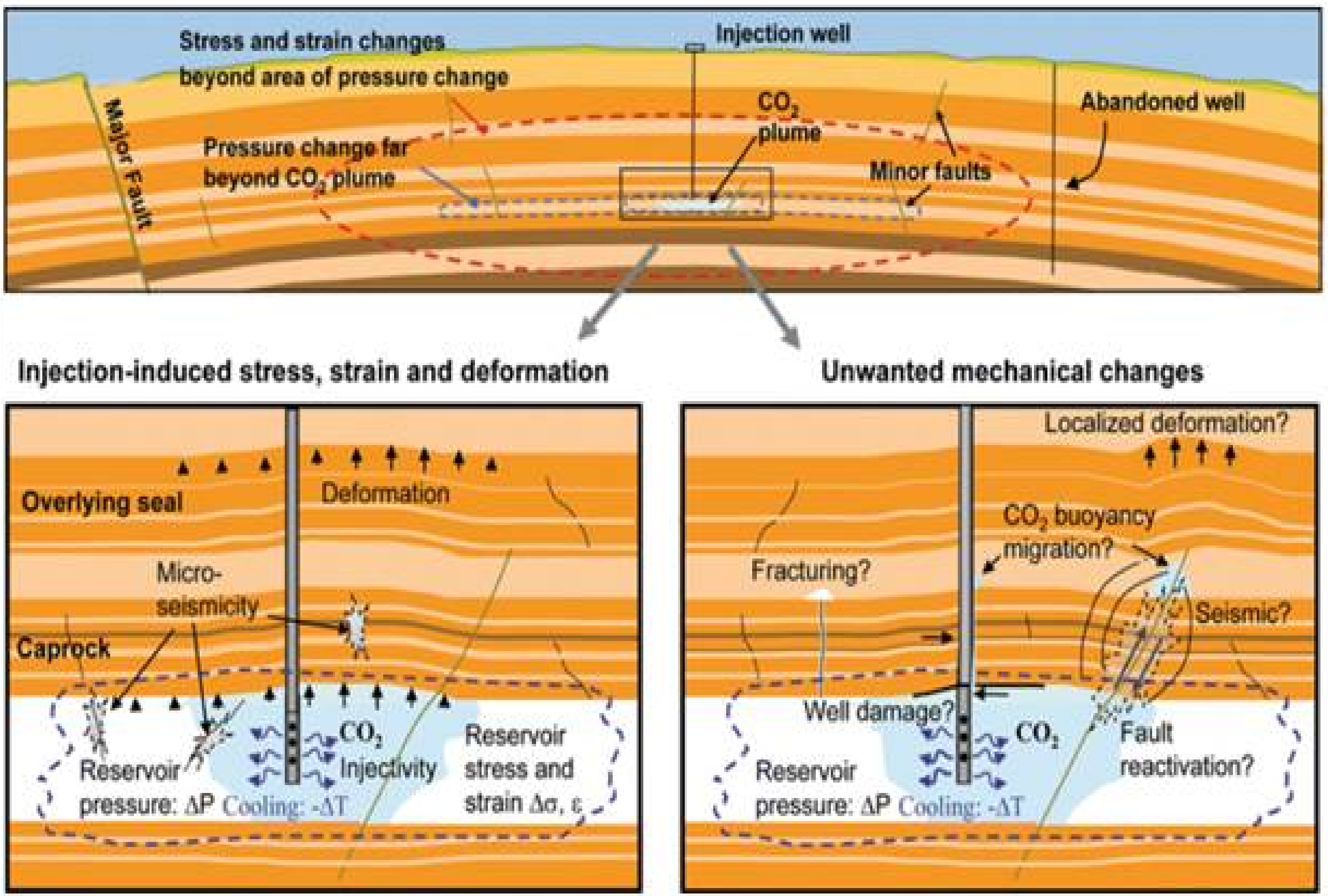
Risk Cost = Probability x Consequences

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

What about tomorrow ?

Geomechanical Processes Associated with Geologic Sequestration of CO_2

Rutqvist (2012)



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Analytical Equations for Induced Shear Stresses

The volumetric strain of a reservoir element, ΔV/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:

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

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

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$$\sigma_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + 2G\varepsilon_{ij} = \lambda\delta_{ij}u_{i,j} + G\left(u_{i,j} + u_{j,i}\right)$$

$$u_x = P\left[\frac{\partial V_1}{\partial x} + 2z\frac{\partial^2 V_2}{\partial x \partial z} + (3-4\nu)\frac{\partial V_2}{\partial x}\right]$$

$$u_y = P\left[\frac{\partial V_1}{\partial y} + 2z\frac{\partial^2 V_2}{\partial y \partial z} + (3-4\nu)\frac{\partial V_2}{\partial y}\right]$$

$$u_z = P\left[\frac{\partial V_1}{\partial z} + 2z\frac{\partial^2 V_2}{\partial z^2} - (3-4\nu)\frac{\partial V_2}{\partial z}\right]$$

Where,

$$P = \frac{(1+\nu)}{12\pi(1-\nu)}\left[C_b\ \Delta P + 3\alpha\Delta T\right]$$

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

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

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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.

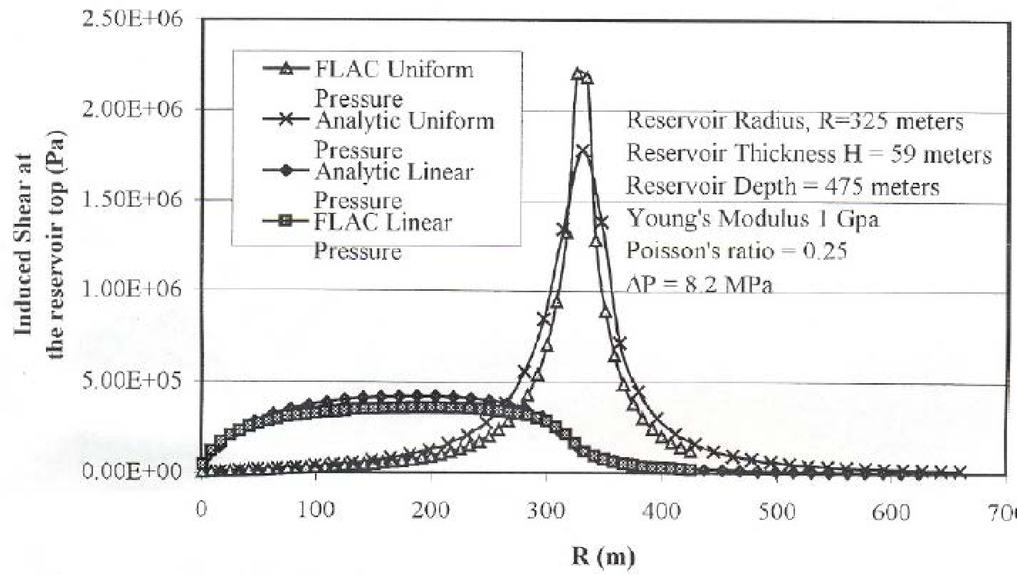


Figure 3. Comparison of induced shear stresses for cases with linear and uniform pressure gradients.

Bruno et. al (1998)

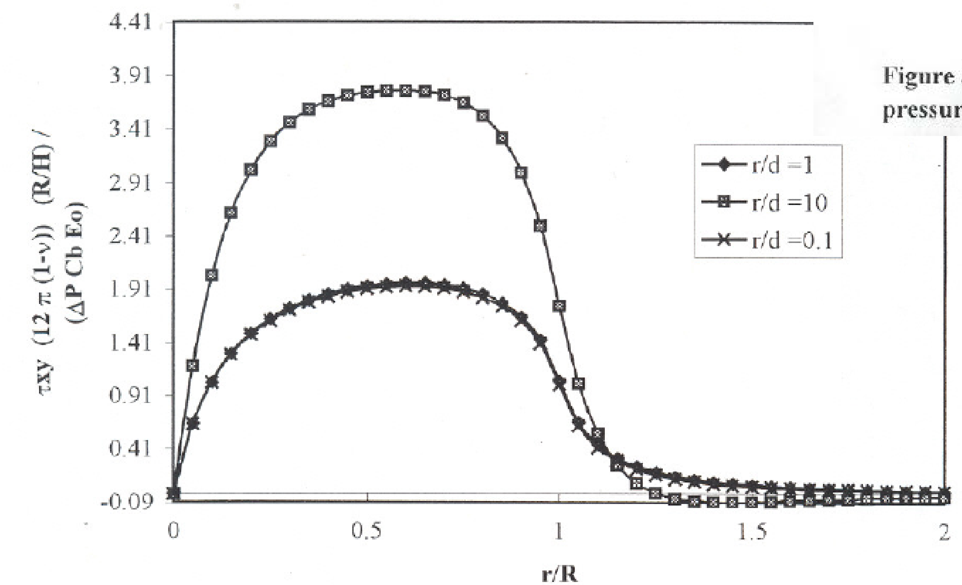
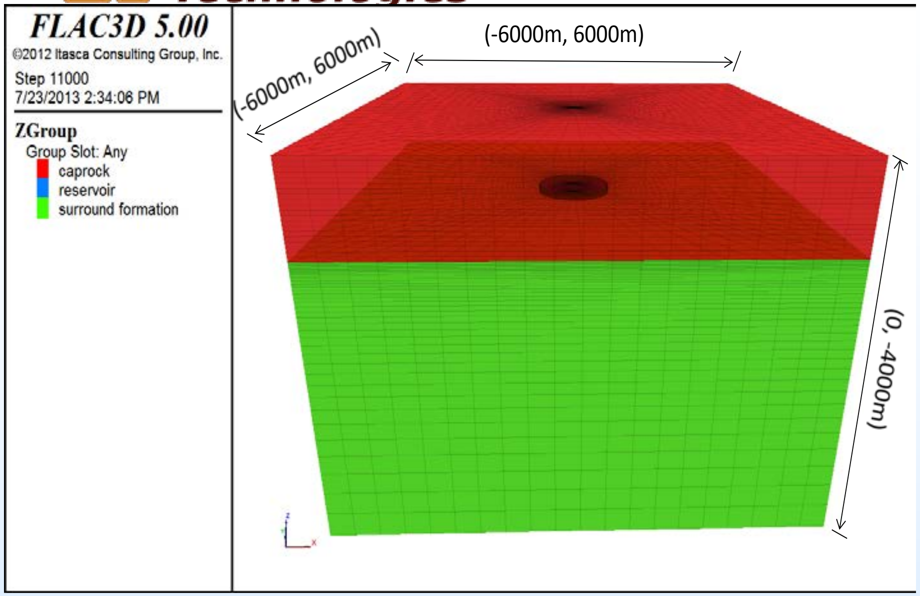


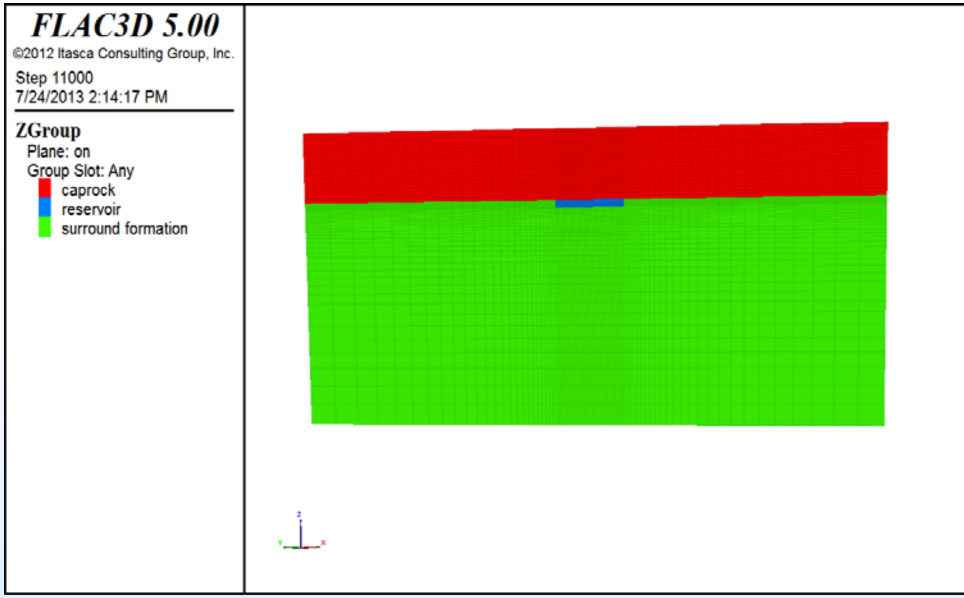
Figure 2. Normalized shear stresses at the top of an axisymmetric reservoir with linear pressure gradient.

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

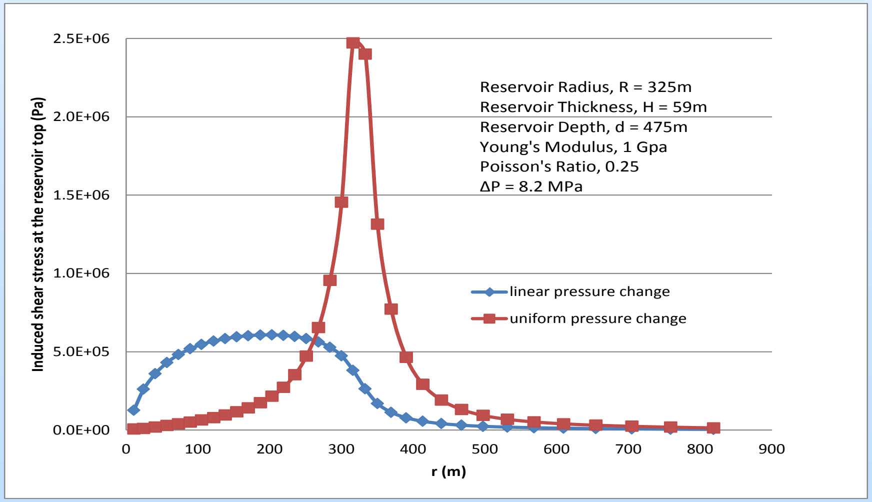
$$\tau_{xz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial x \partial z} + 2z \frac{\partial^3 V_2}{\partial x \partial z^2} + \frac{\partial^2 V_2}{\partial x \partial z} \right] dV$$

Numerical Model for Caprock Integrity Study

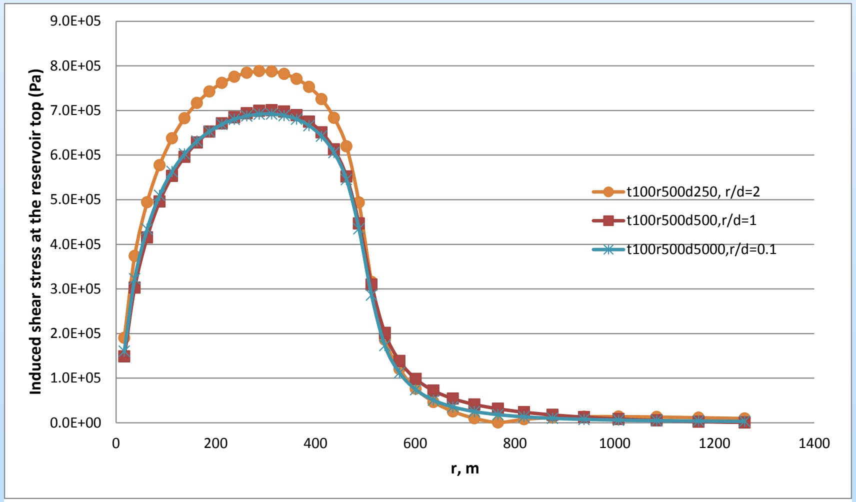




(Left) 3D geomechanical model used to study induced shear stress in caprock; (Right) Section view through center of model.



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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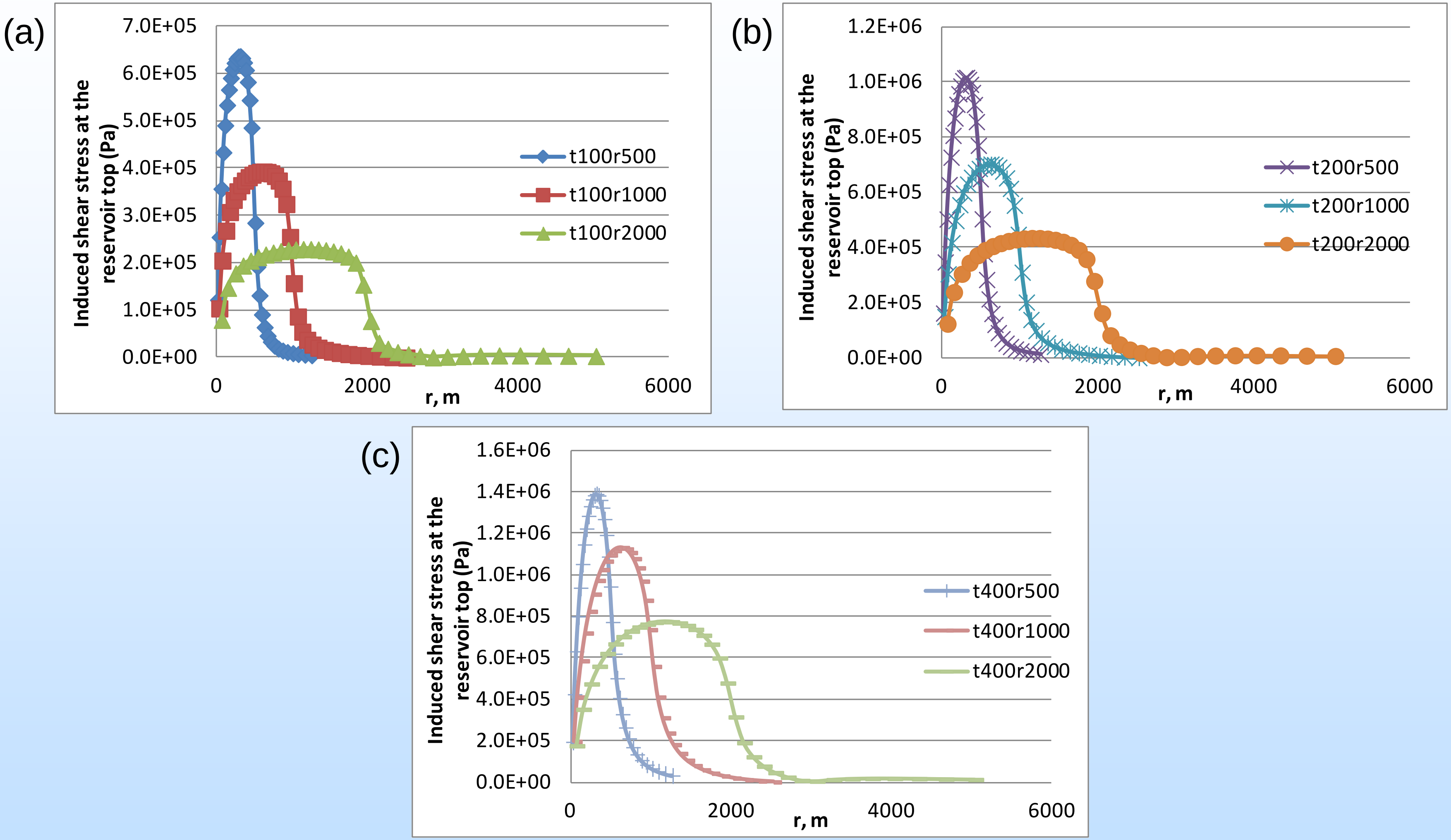
Varying Reservoir Thickness & Radius



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.

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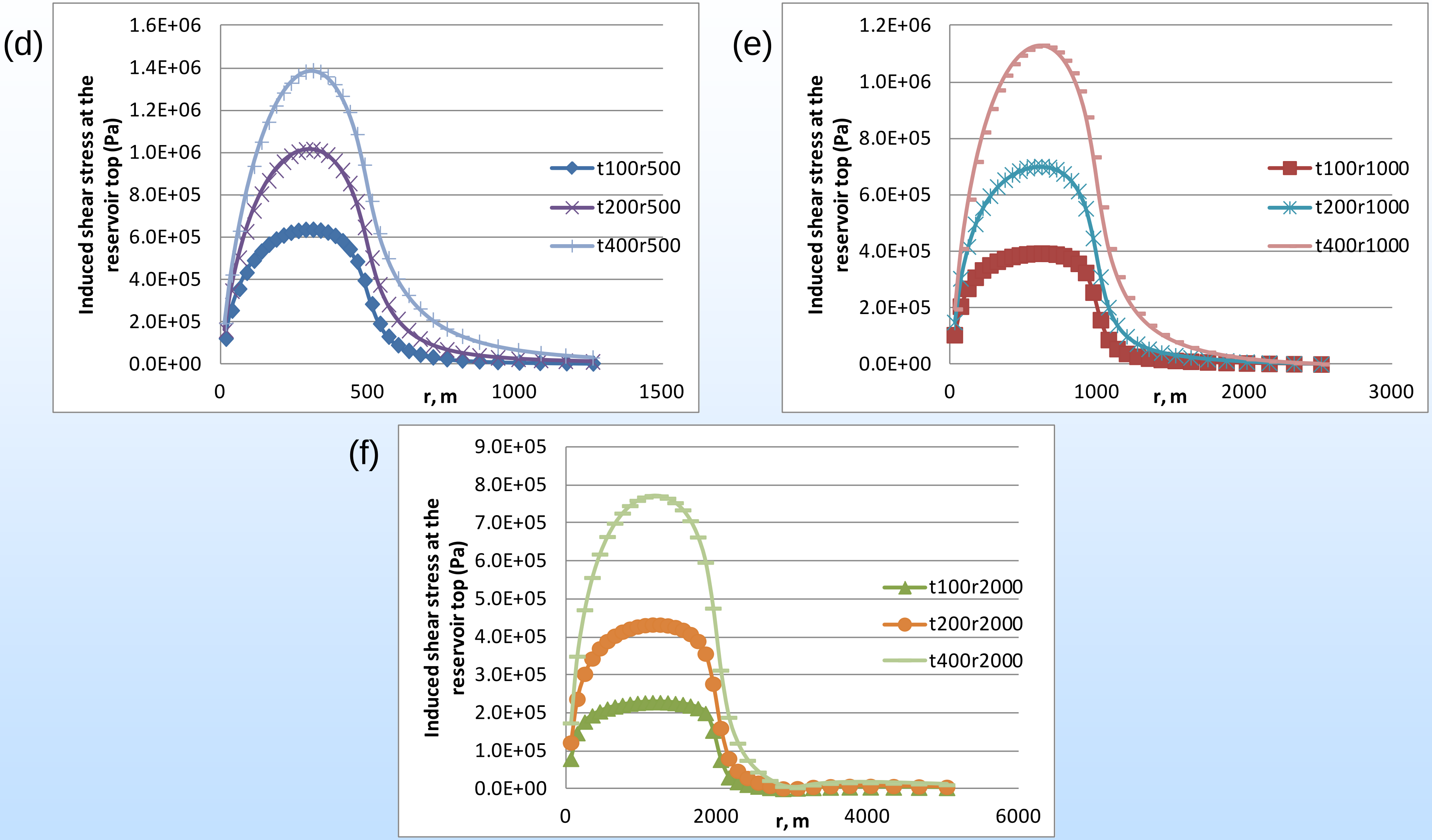

Induced shear stress in the caprock with (d) 500m, (e) 1000m, and (f) 2000m reservoir radius while changing reservoir thickness from 100m to 400m under linear pressure change.

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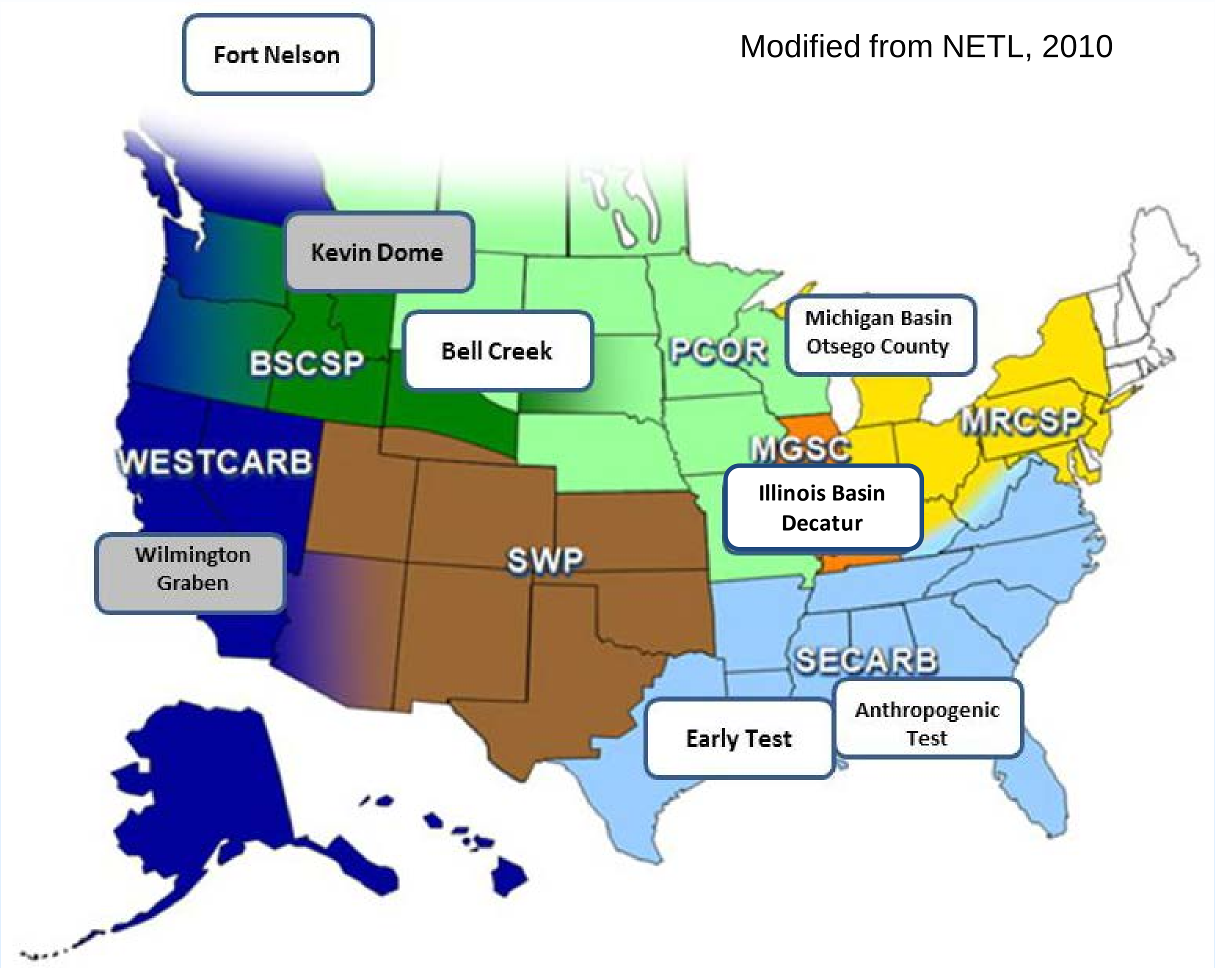
Analytical and Numerical Analyses Proceeding For:

1. Louden Field
2. Wilmington Graben CO_2 Site
3. Kevin Dome CO_2 Site

Includes:

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

North America Large Scale CO2 Characterization Projects



Map showing all 7 RCSP development-phase projects. Selected projects for this study (highlighted in gray) include the Wilmington Graben Characterization Project and Kevin Dome CO2 Injection Projects.

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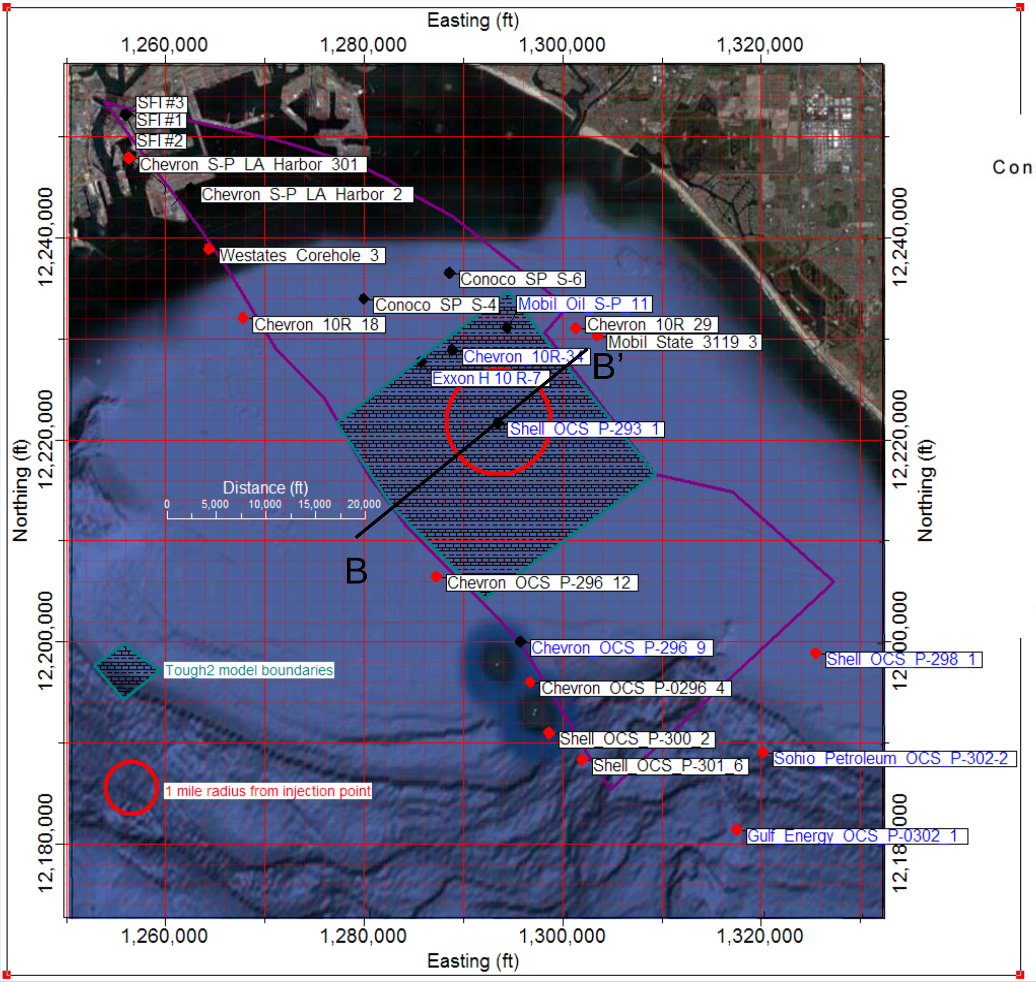
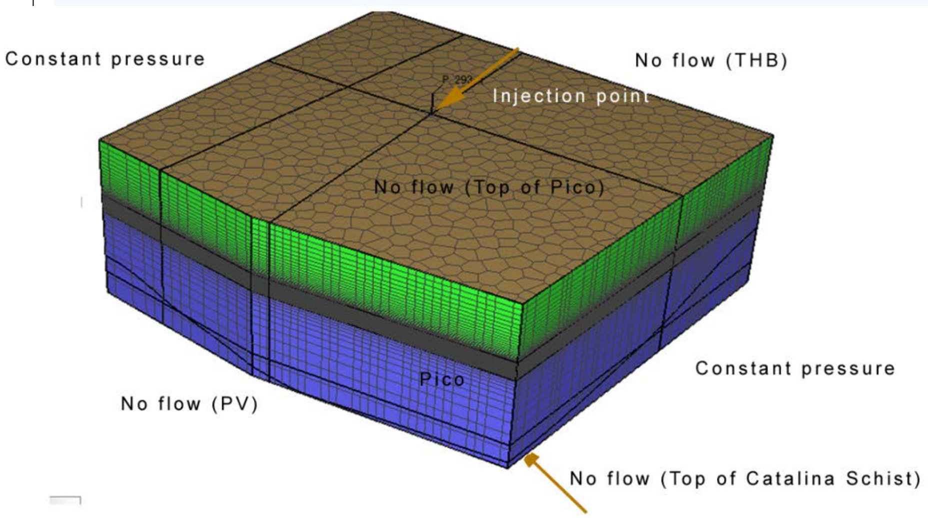
3D Fluid Flow and GeoMechanical Models for Caprock Integrity





(Left) Map of Wilmington Graben Characterization Project located offshore near Long Beach, California. (Top Right) Fluid Flow Model with Tough2 Code. (DOE Project number: FE0001922)

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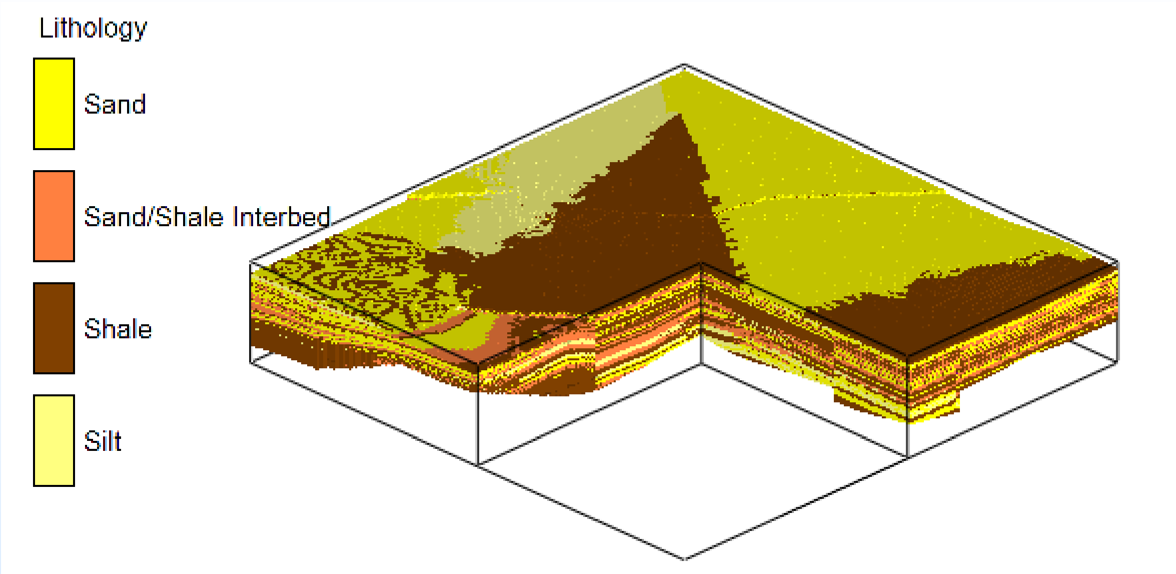
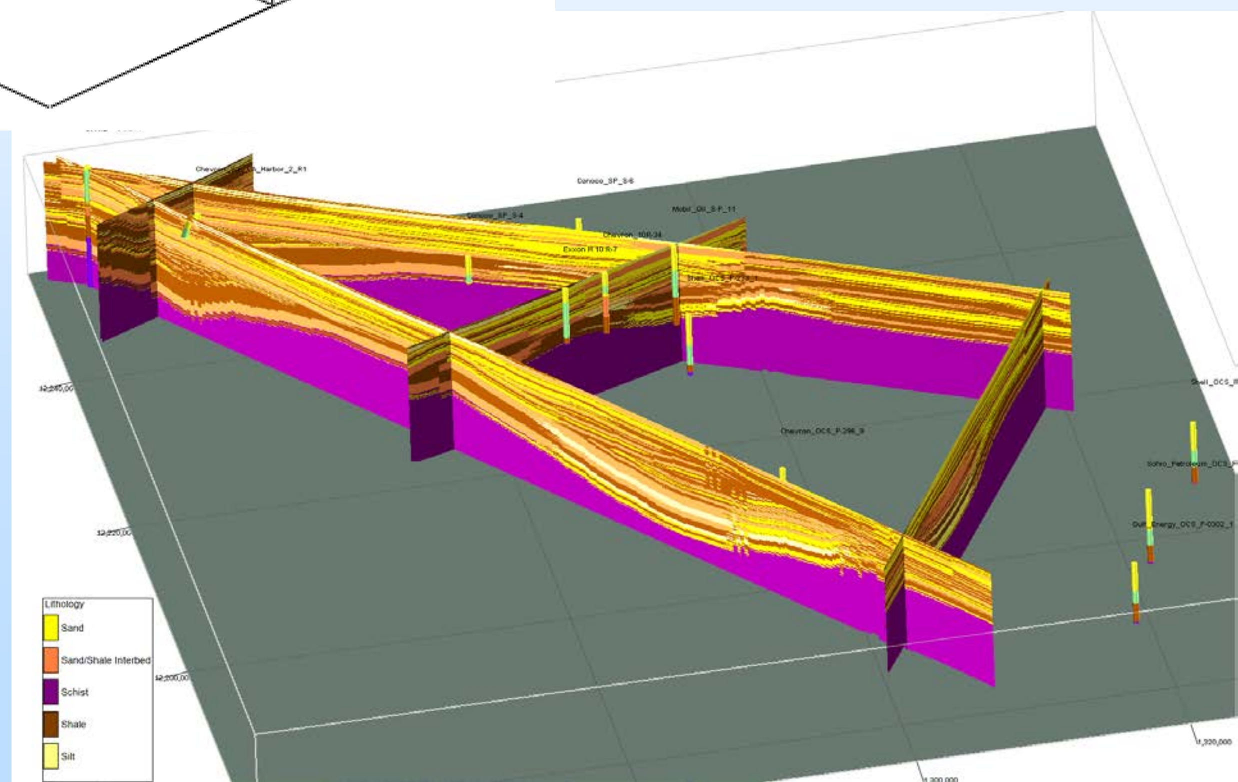
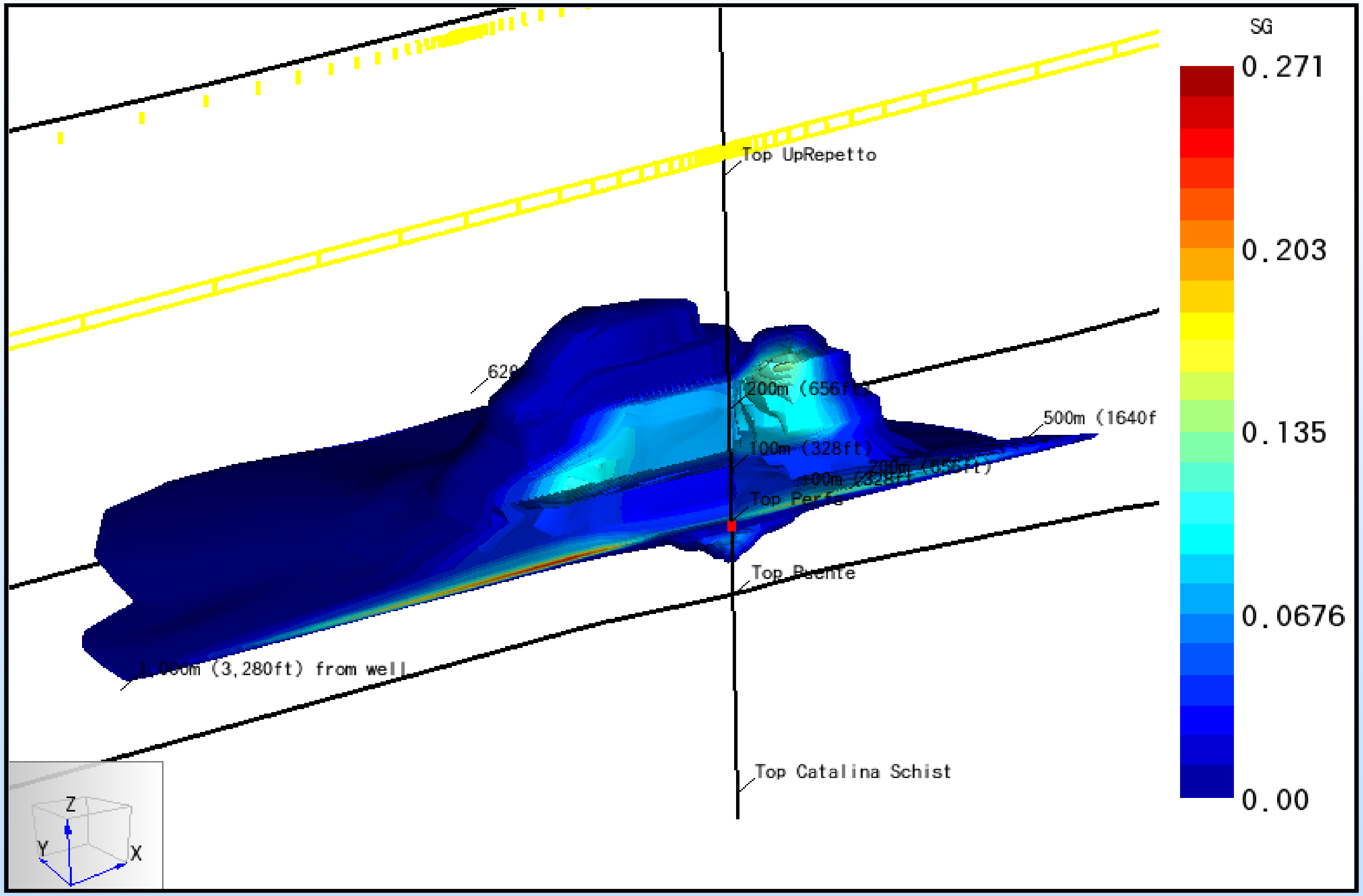
Geologic Model of Wilmington-Graben



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



CO2 Injection and Migration Modeling at Wilmington-Graben

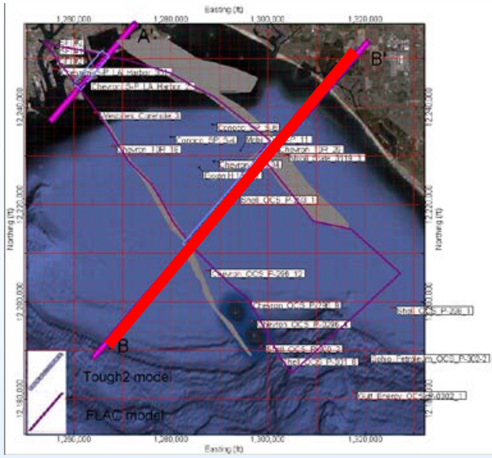


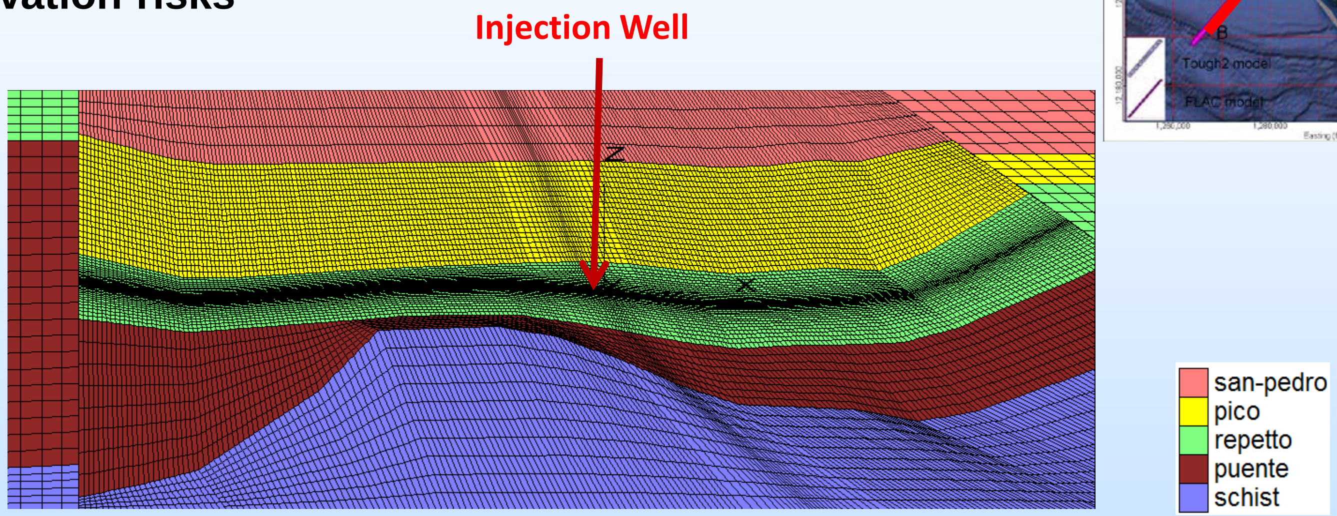
CO2 Plume after 55 yrs (B-B') at 1MM mt/yr
migrated 1000m horizontally & 350m vertically

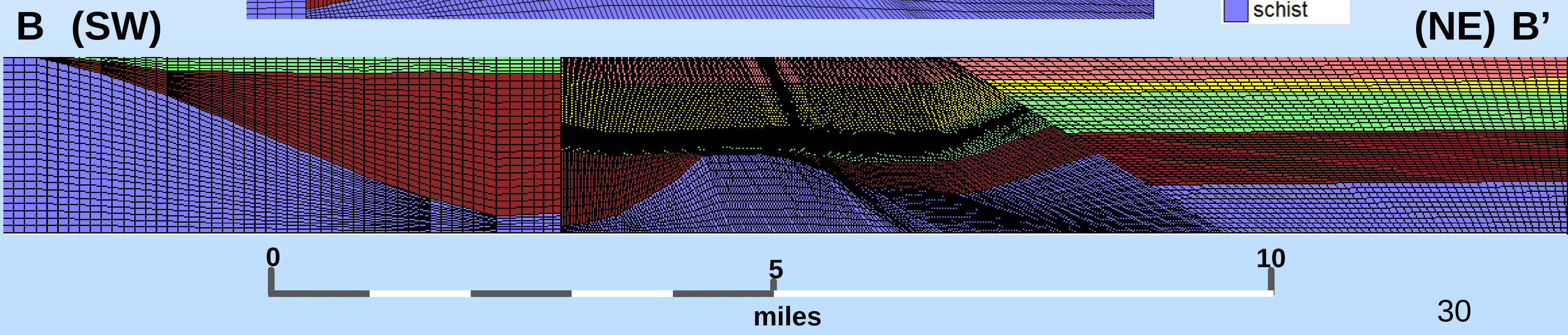
3D Geomechanical Model for B-B' Section at Wilmington-Graben

Develop Geomechanical Model to Assess:

1. **Caprock Integrity**
2. **Induced deformations & stresses**
3. **Fault activation risks**







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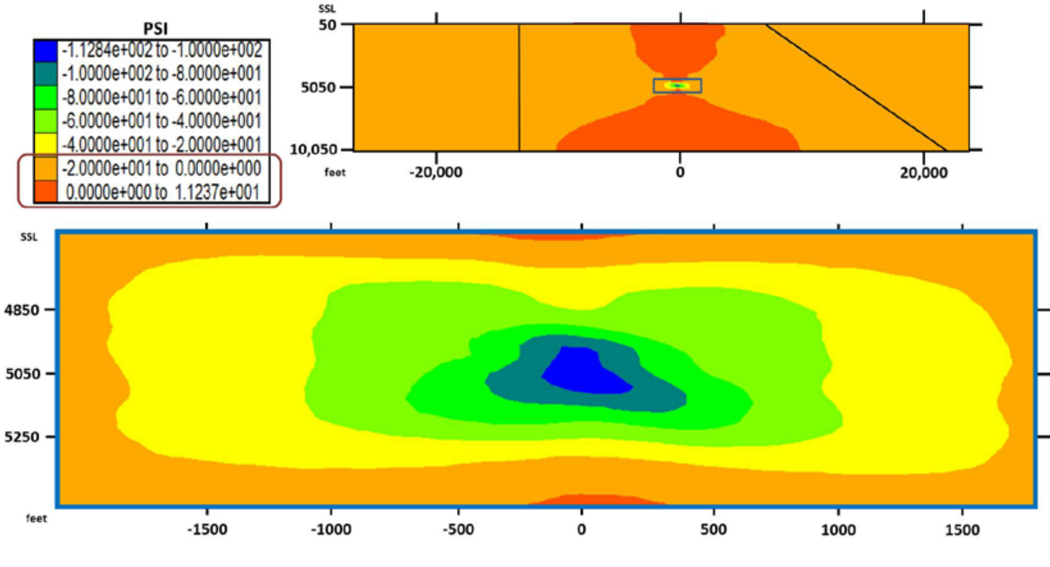
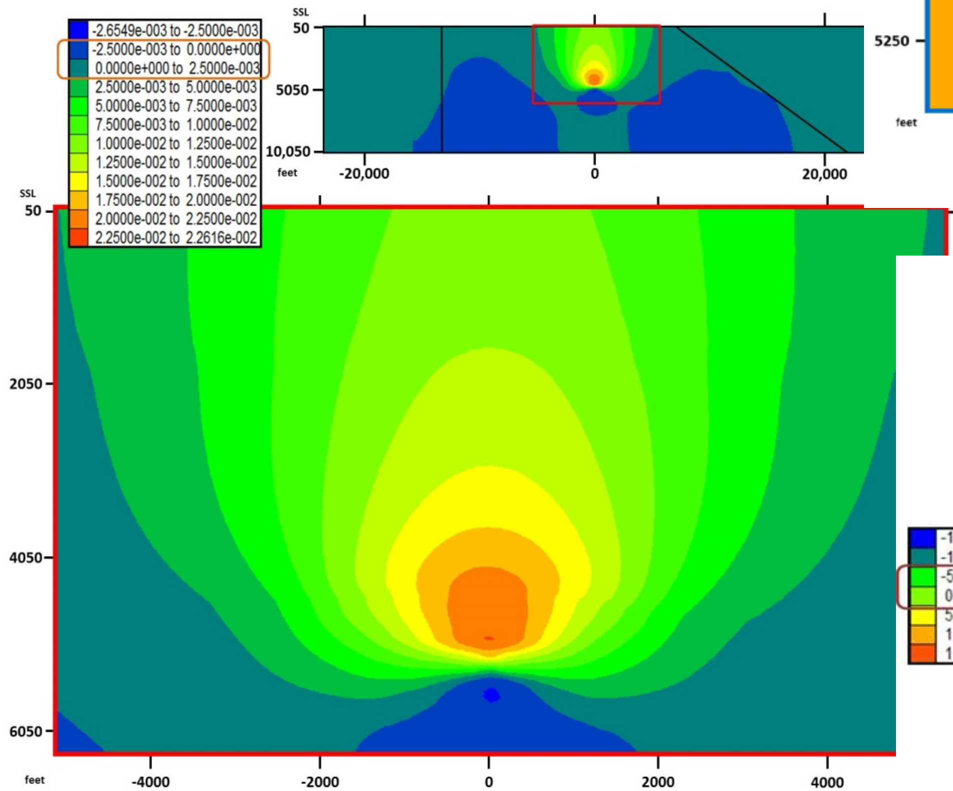
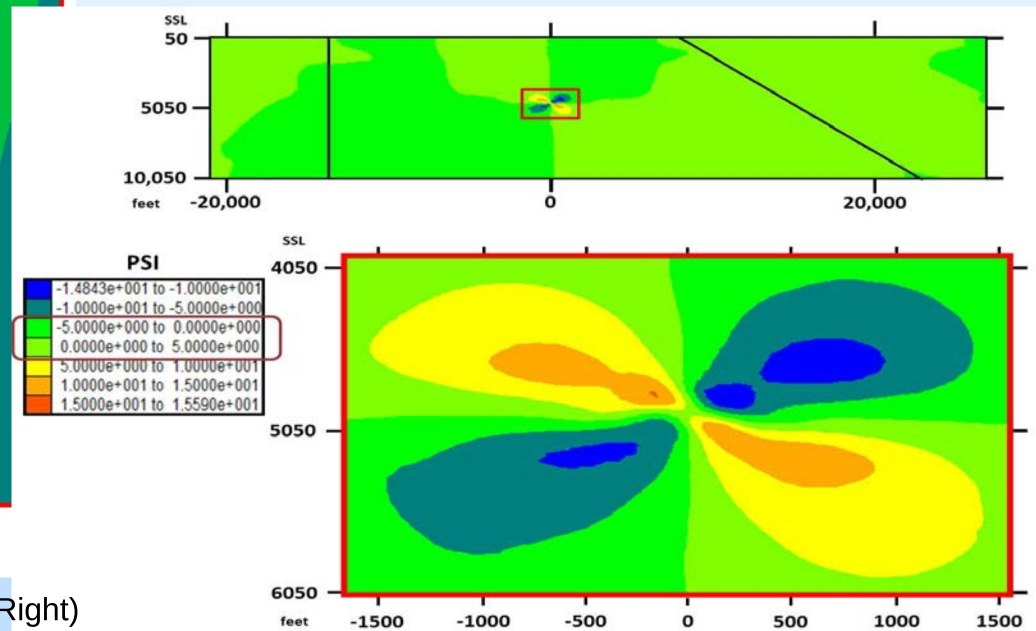
Induced stresses and deformations are limited to within few miles. No fault activation is observed.



Contour of SXX



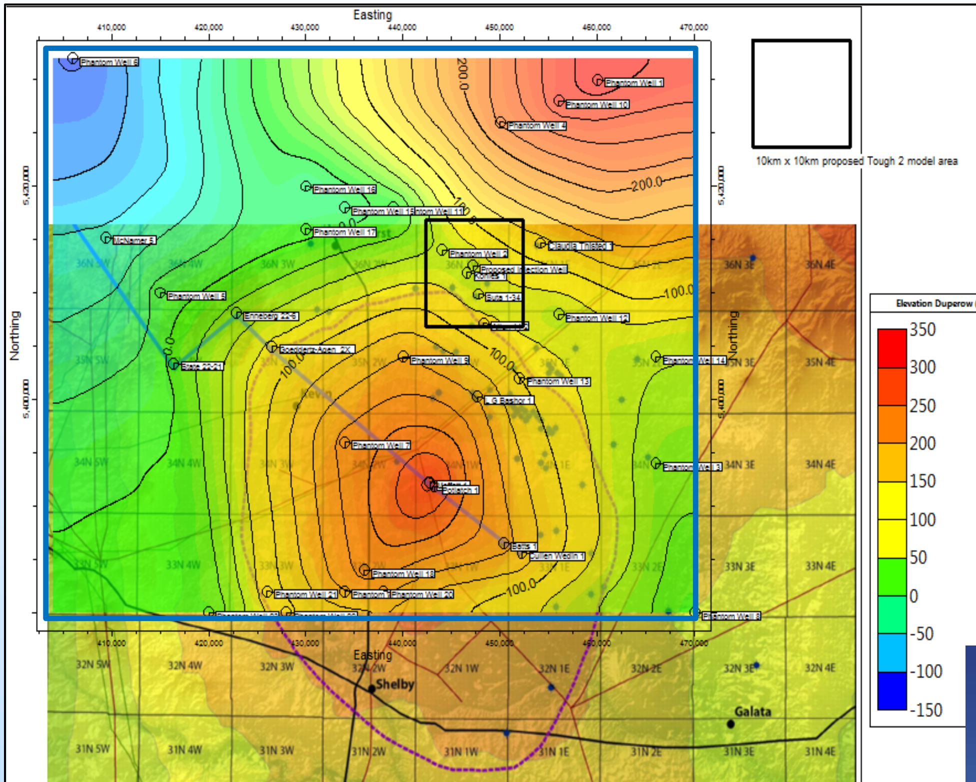
Contour of Z-Displacement

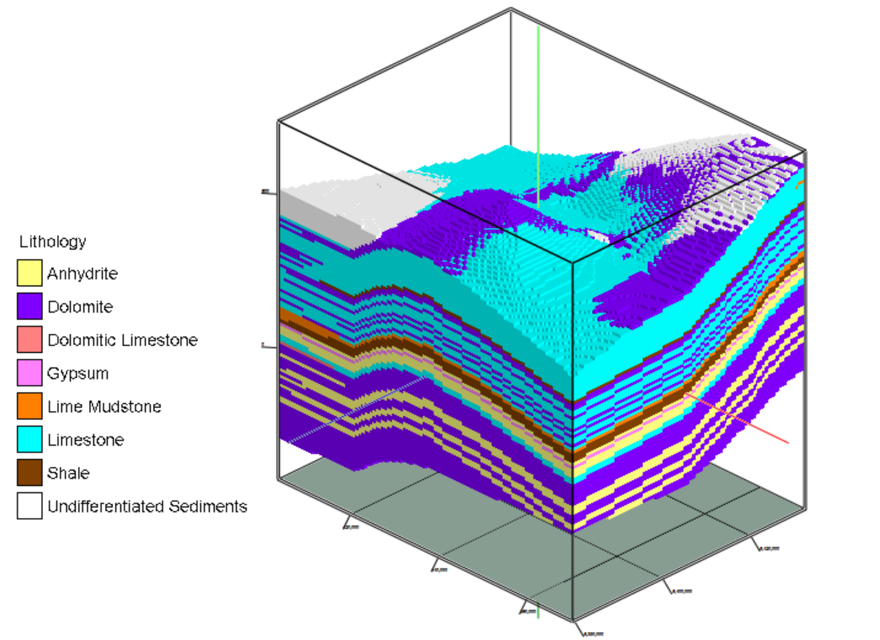


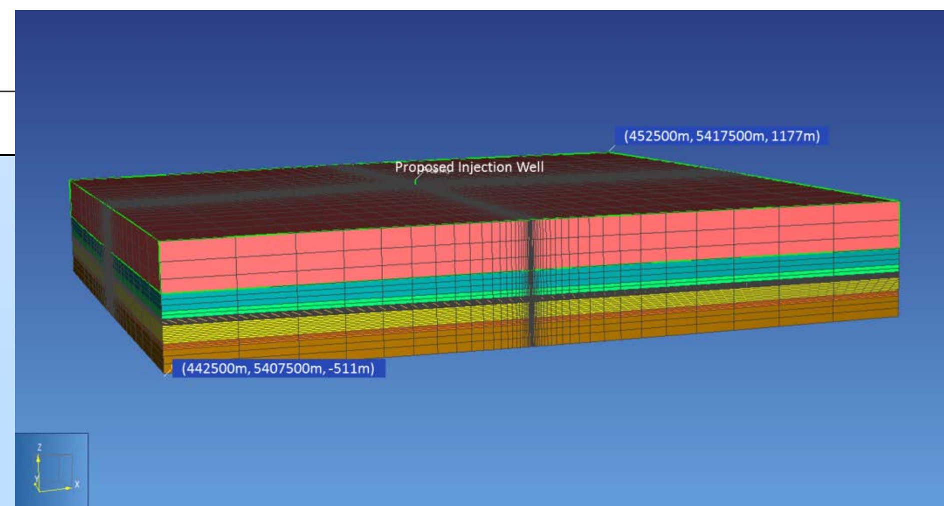
Contour of SXZ

(Right) Contour plots of induced horizontal stress; (Bottom Right) induced shear stress; and (Bottom Left) induced vertical displacement after 1 month of quarter-million MT/year of CO_2 injection.

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.

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Risk Cost = Probability of Event x Economic Consequence

<u>Quantitative Risk Analysis Methodology</u>

Estimate Likelihood of Loss Events;

Evaluate Consequences; and

Compare Risk Cost to Benefits.

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Factors Decreasing Risk:

Caprock Thickness
Collector Zones Above Caprock
Multiple Seals and Sinks
Increasing Depth
Offshore

Factors Increasing Risk:

Areal Extent
Pressure and Thickness
Higher Number of Wells
Well Damage History
Population
Onshore
Tectonic Setting

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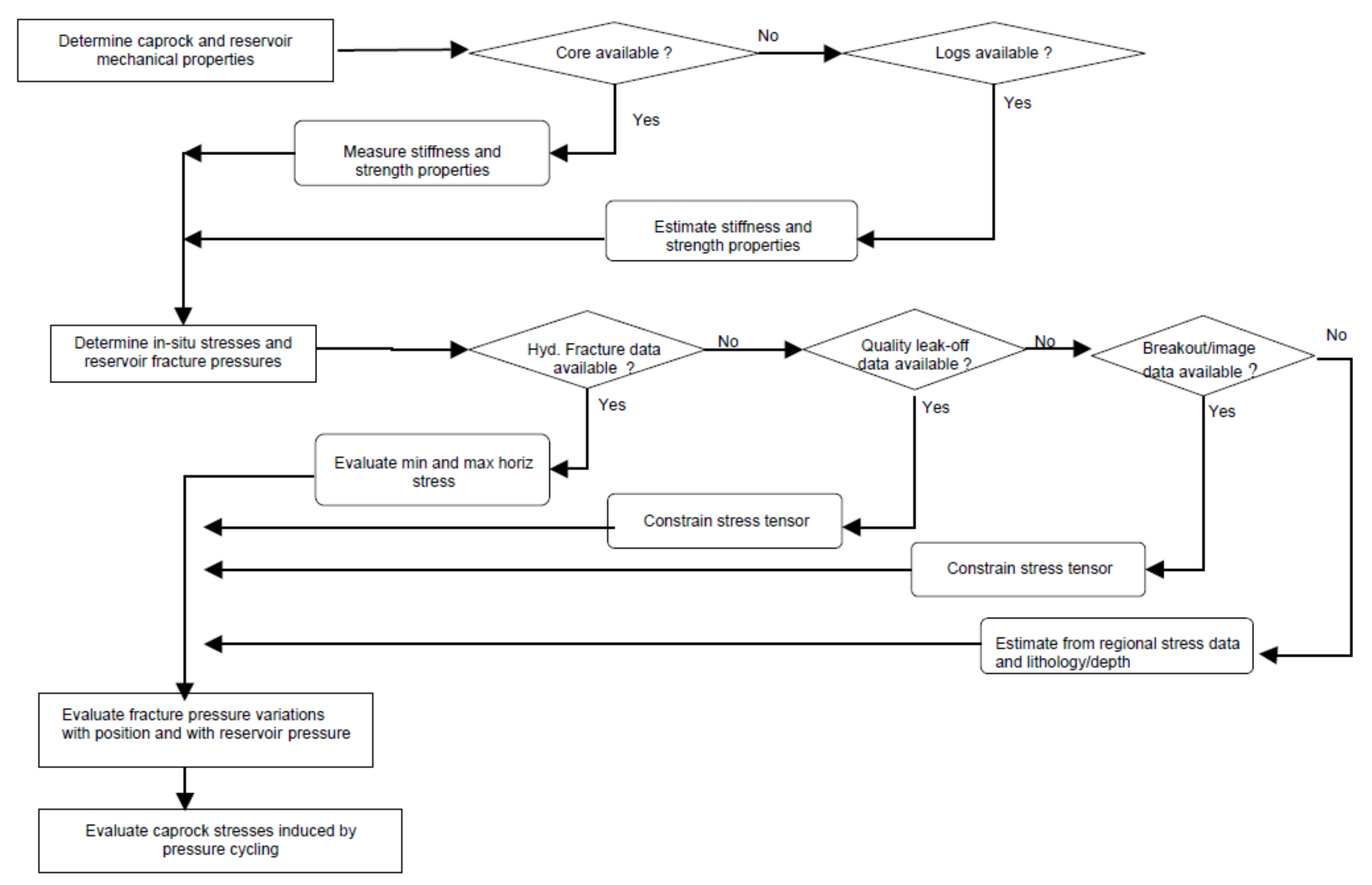

Example of step-by-step process to evaluate geomechanical limits for caprock integrity induced by large scale CO_2 injection.

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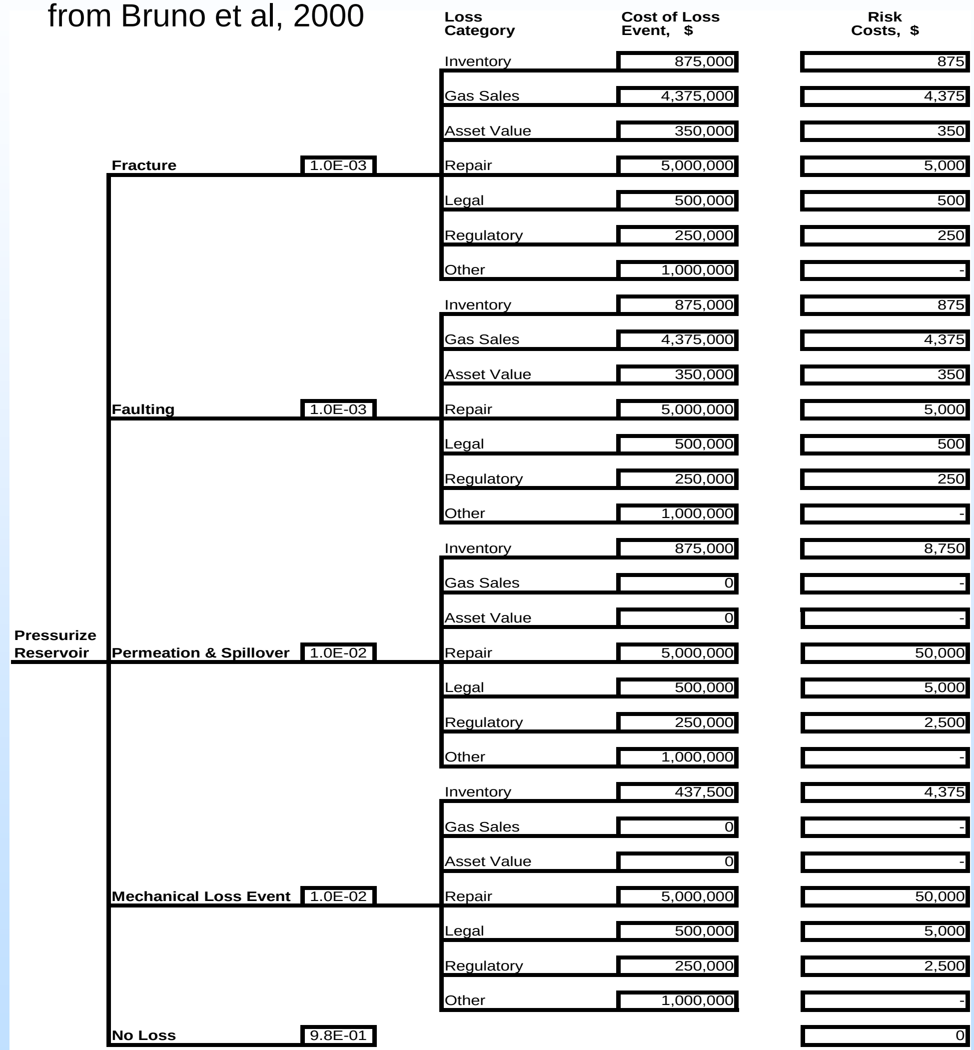
3.0 Reservoir Properties									
Largest Lateral Dimension (m)	3500								
Reservoir Thickness (m)	140								
Caprock Thickness (m)	383								
Collector Zone:	>10 zones								
Multiple collector zones	1	1	1	1	1	1	1	1	1
One collector	0	10	0	10	0	10	0	10	0
No collector zones	0	100	0	100	0	100	0	100	0
Fault Boundaries									
None	1	1	1	1	1	1	1	1	1
One	0	1	0	10	0	10	0	10	0
More than one	0	1	0	100	0	100	0	100	0
Caprock Seal	383								
Thickness >= 30m	1	1	1	1	1	1	1	1	1
3m < Thickness <30m	0	10	0	10	0	10	0	1	0
Thickness <= 3m	0	100	0	100	0	100	0	1	0
Caprock Strength									
Strong	0	1	0	1	0	1	0	1	0
Moderate	1	1	1	10	10	1	1	10	10
Weak	0	1	0	100	0	1	0	100	0
Reservoir Homogeneity									
Low	0	1	0	1	0	1	0	1	0
Moderate	1	10	10	10	10	10	10	1	1
Significant	0	100	0	100	0	100	0	1	0
Ratio Reservoir Lateral Dimension/Formation Depth	2.02								
Less than or equal to 1	0	1	0	1	0	1	0	1	0
Between 1 and 10	1	10	10	10	10	1	1	10	10
Greater than or equal to 10	0	100	0	100	0	1	0	100	0
Ratio Reservoir Thick/Depth	0.08								
Less than or equal to 0.1	1	1	1	1	1	1	1	1	1
Between 0.1 to 0.5	0	10	0	10	0	1	0	10	0
Greater than or equal to 0.5	0	100	0	100	0	1	0	100	0
CATEGORY SCORE	**100**		25		34		16		25
TOTAL SCORE	**232**								

Sample Risk Assessment Tool

2.0 State of Stress									
Minimum Stress Known? (1=yes, 0=no)	1								
Minimum in-situ Stress	2000								
Desired Max Pressure/ Min Stress	0.7								
Less than or equal to 0.5	0	1	0	1	0	1	0	1	0
Between 0.5 and 0.75 inclusive	1	10	10	10	10	10	10	10	10
Greater than 0.75 or unknown	0	100	0	100	0	100	0	100	0
Regional Stress Conditions:									
Normal stress orientation	0	1	0	1	0	1	0	1	0
Strike-slip stress orientation	1	10	10	10	10	10	10	10	10
Thrust-fault orientation	0	100	0	100	0	100	0	100	0
Local Seismic History									
Low activity	1	1	1	1	1	1	1	1	1
Moderate activity	0	10	0	10	0	10	0	10	0
High activity	0	100	0	100	0	100	0	100	0
CATEGORY SCORE	84		21		21		21		21
3.0 Reservoir Properties									
Largest Lateral Dimension, LD, ft	15000								
Reservoir Thickness, ft	10								
Caprock Thickness, ft	15								
Collector Zone:									
Multiple collector zones	0	1	0	1	0	1	0	1	0
One collector	0	10	0	10	0	10	0	10	0
No collector zones	1	100	100	100	100	100	100	100	100
Fault Boundaries									
None	1	1	1	1	1	1	1	1	1
One	0	1	0	10	0	10	0	10	0
More than one	0	1	0	100	0	100	0	100	0
Caprock Seal									
Thickness >= 100 ft	0	1	0	1	0	1	0	1	0
10 < Thickness < 100 ft	1	10	10	10	10	10	10	1	1
Thickness < = 10 ft	0	100	0	100	0	100	0	1	0
Caprock Strength									
Strong	0	1	0	1	0	1	0	1	0
Moderate	1	1	1	10	10	1	1	10	10
Weak	0	1	0	100	0	1	0	100	0
Reservoir Homogeneity									
Low	0	1	0	1	0	1	0	1	0
Moderate	1	10	10	10	10	10	10	1	1
Significant	0	100	0	100	0	100	0	1	0
Ratio Reservoir Lateral Dimension / Formation Depth	6.00								
Less than or equal to 1	0	1	0	1	0	1	0	1	0
Between 1 and 10	1	10	10	10	10	1	1	10	10
Greater than or equal to10	0	100	0	100	00	1	0	100	0
Ratio Reservoir Thick / Depth	0.004								
Less than or equal to 0.1	1	1	1	1	1	1	1	1	1
Between 0.1 and 0.5	0	10	0	10	0	1	0	10	0
Greater than or equal to 0.5	0	100	0	100	0	1	0	100	0
CATEGORY SCORE	514		133		133		124		124
TOTAL SCORE	1204		256		265		346		346

from Bruno et al, 2000



Illustrative Examples of Likelihood Evaluation and Risk Assessment Tool for Caprock Integrity.

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Project Status and Accomplishments to Date (9 months):

- Completed Historical Data Review & Documentation of Caprock Integrity in both U.S. and European Gas Storage Industry
- Completed analytical description and comparison numerical simulations describing caprock stresses induced by CO_2 injection
- Assembled 3D Geologic Models, Fluid Flow Models, and Geomechanical models for three sample fields (Wilmington-Graben, Kevin Dome, Louden).

Appendix

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

Team Members

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

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Gantt Chart