Project: DE-FE0001836:

Numerical modeling of geomechanical processes related to CO_2 injection within generic reservoirs

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U.S. Department of Energy

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

August 21-23, 2012

Presentation Outline

- Objectives, Benefits and Outcomes
- Technical status: Project summary
  - Teaching
  - Reservoir scale (Geomechanics & Fluid flow simulation)
  - Borehole scale (Wellbore integrity & wellbore trajectory planning)
- Conclusions
- Appendix

Benefit to the Program

- Program goals being addressed.
  - Develop technologies that will support industries' ability to predict storage capacity in geologic formations to within 30 percent.
- Project benefits statement:
  - This research & training project is training graduate students to develop numerical models of anticline formations for sequestration sites in order to assess geomechanical risks as well as critical wellbore placement and wellbore integrity. The results give a more thorough understanding of how reservoir geometry affects wellbore stability, formation and cap rock stability and thus facilitates future site selection. This technology contributes to the Carbon Storage Program's effort that will support industries' ability to predict storage capacity in geologic formations to within 30 percent.

Project Overview: Goals and Objectives

Goals & Objectives

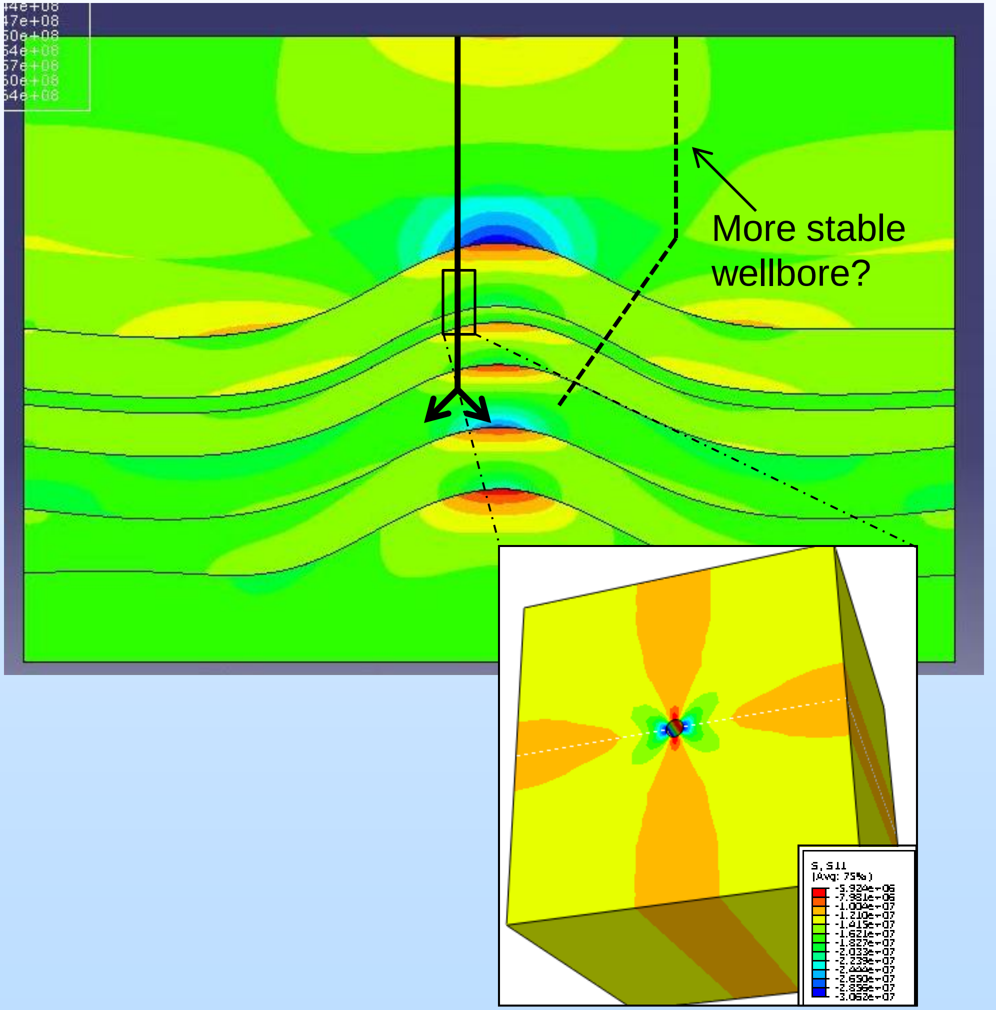
- Train graduate students to develop multi-scale numerical models (finite element models and finite difference models.
- Assess geomechanical risks (with respect to how fluid pressure induces rock deformation): reservoir and cap rock stability, wellbore stability, wellbore trajectory optimization.

Success criteria

- 400 level graduate course on “Advanced Finite Element Analysis with CO2 applications” – *participating students enrolled & passed*.
- Milestones, quarterly progress reports, presentations and publications.

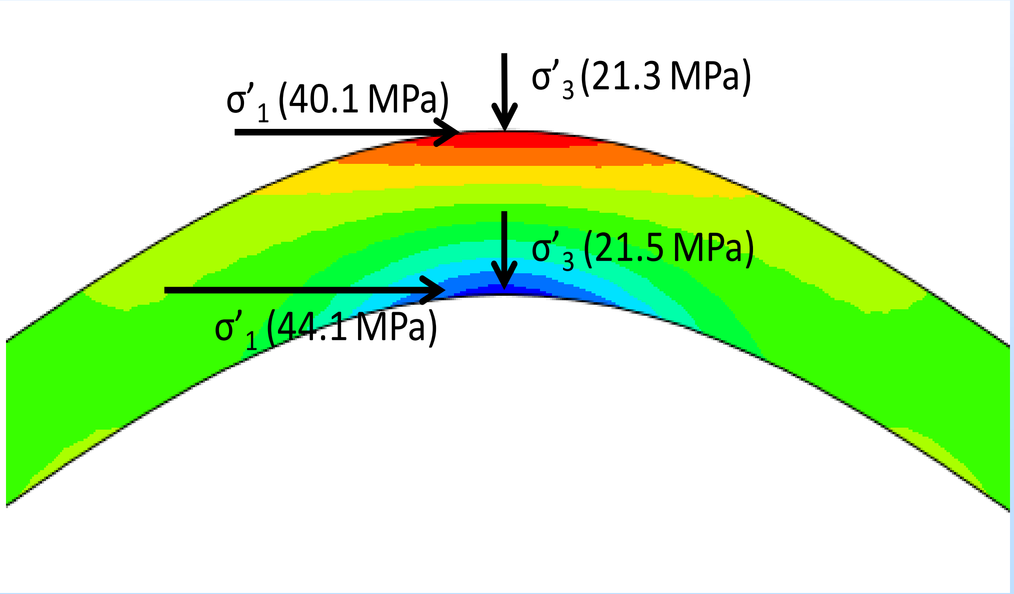
Technical Approach: Methodology

- Multi-scale modeling to study influences of large scale models on borehole
  - Optimal wellbore trajectory
  - Optimal wellbore design



Stress in the Anticline

- Antiformal structures are prime injection targets
  - Stress state is altered by the geometry
  - Varying the geometry will alter the injectivity



Pre-injection geomechanical risk assessment: Objectives

- Develop of reservoir scale finite element model of generic anticline structures
- Perform critical pore pressure (CPP) analysis
- Determine the influence of certain geometric and geologic parameters on CPP
  - Anticline Wavelength
  - Anticline Amplitude
  - Stress Regime

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Workflow

Altair Hypermesh® to build geometries

Input boundary and initial conditions

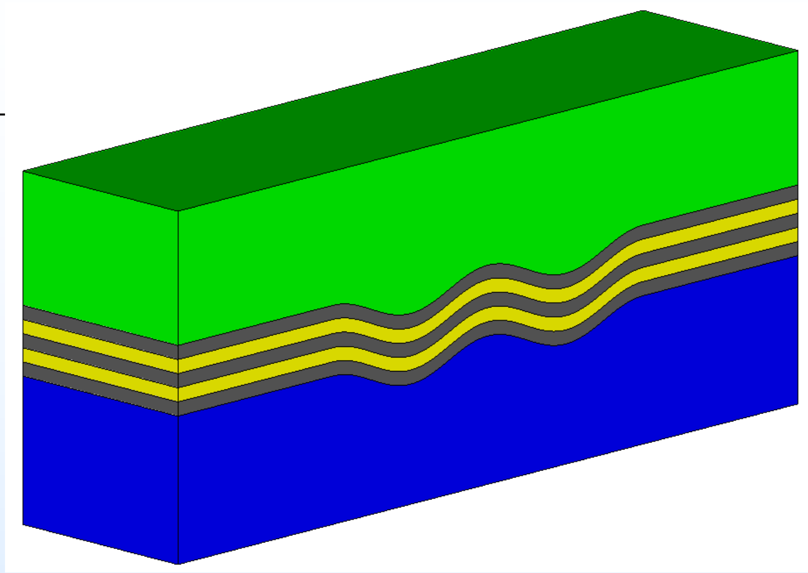
Abaqus/Standard® to process finite element models

Abaqus/Viewer® to view results

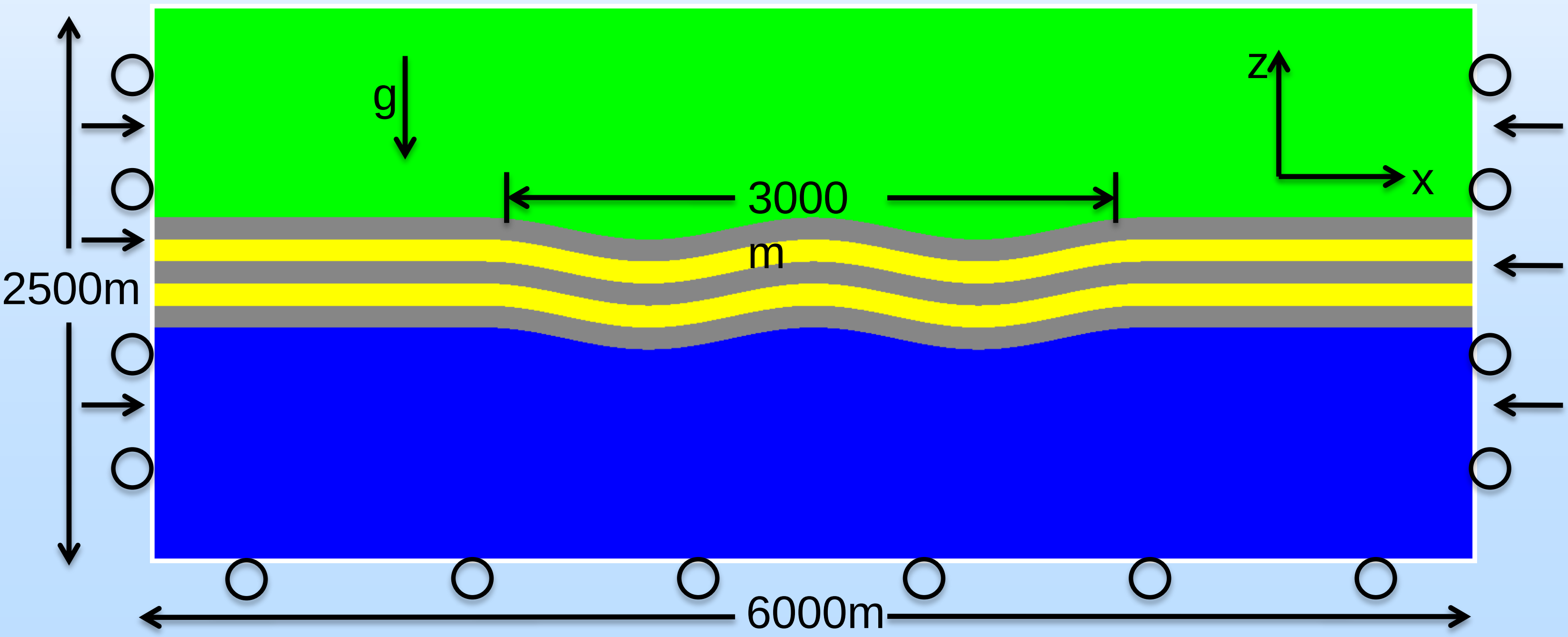
Matlab® for data processing

Microsoft Excel® to analyze data

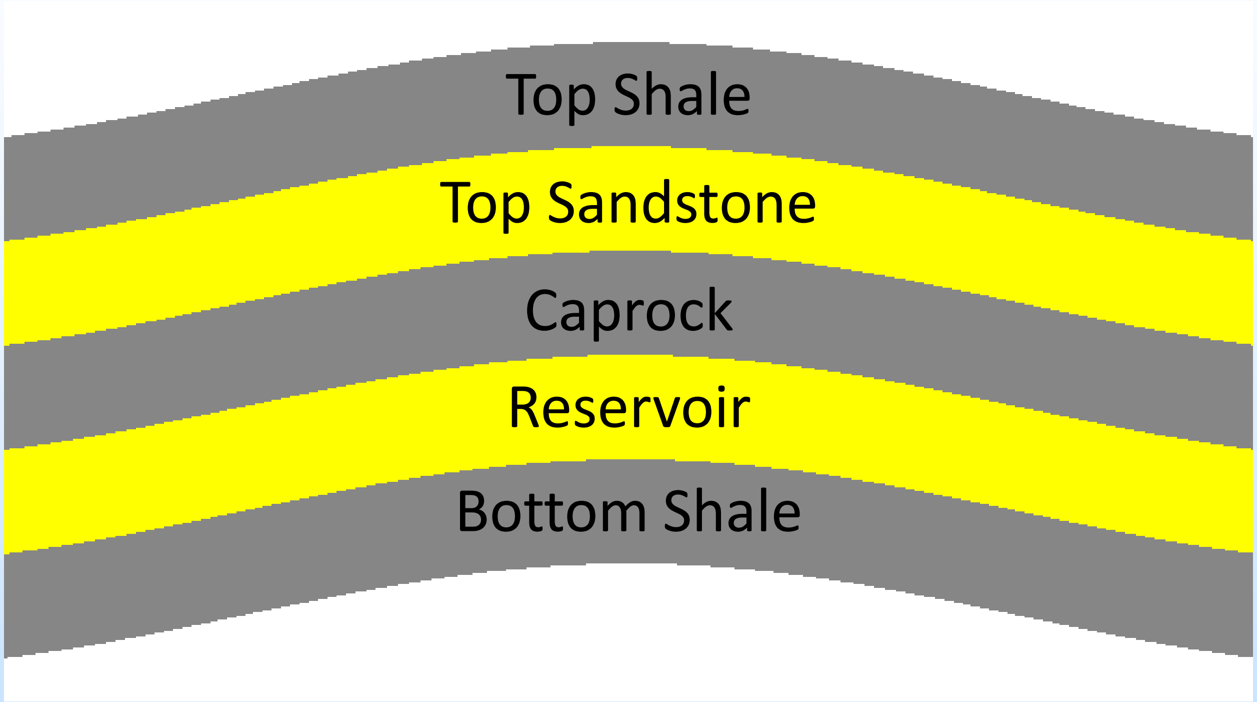
Model Setup



- Constructed using Altair HyperMesh™



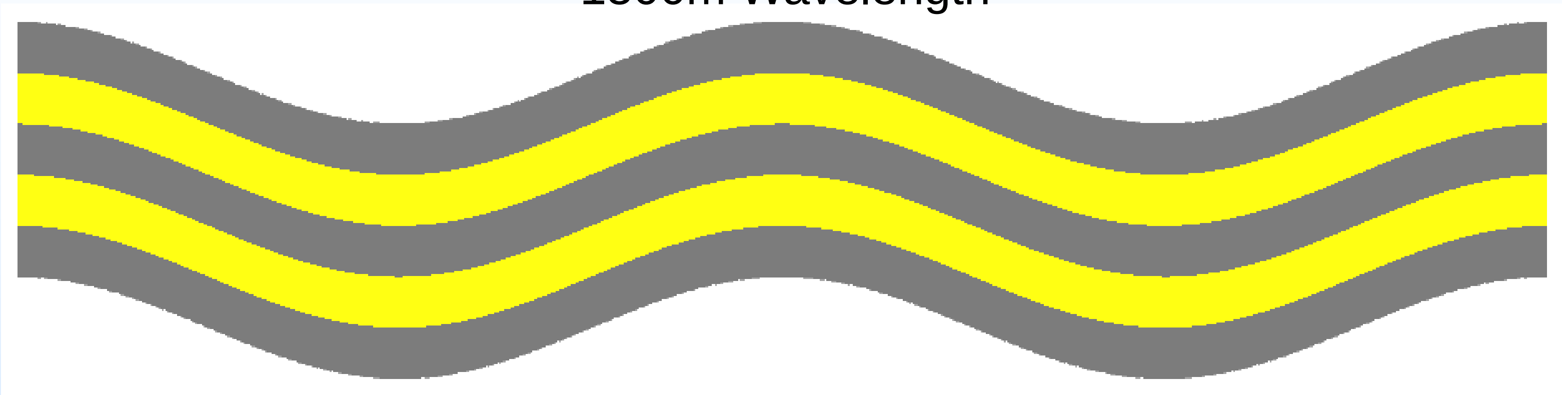
Reservoir-Caprock System



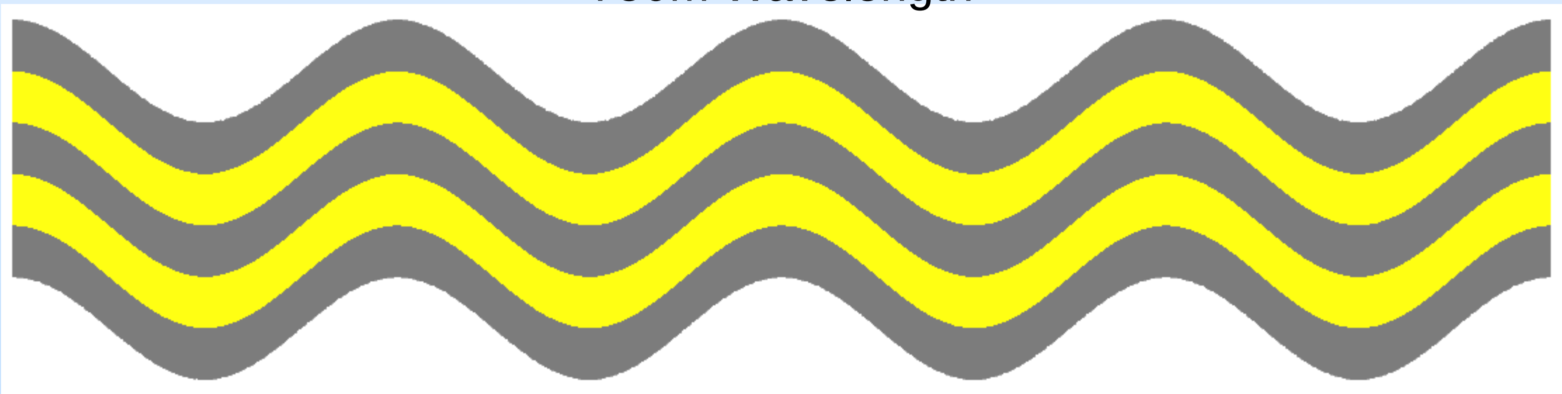
- Calculations of critical pore pressure done for reservoir and caprock layers

Varying Anticline Wavelength

1500m Wavelength



750m Wavelength



3000 m

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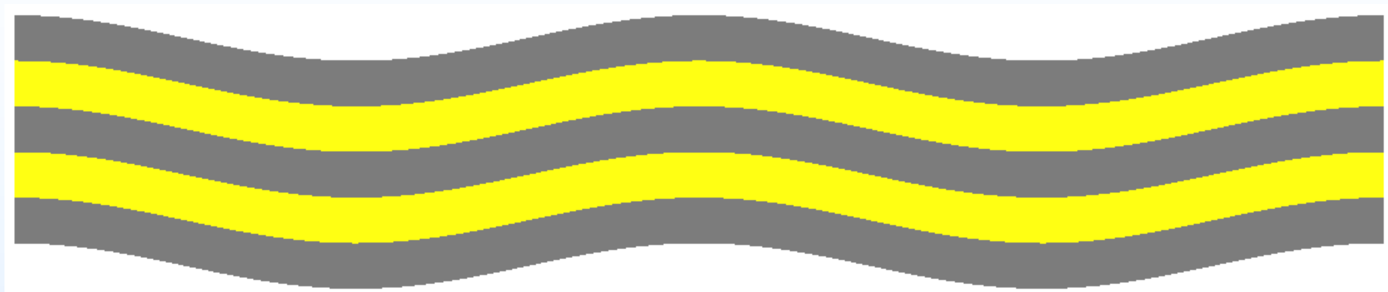
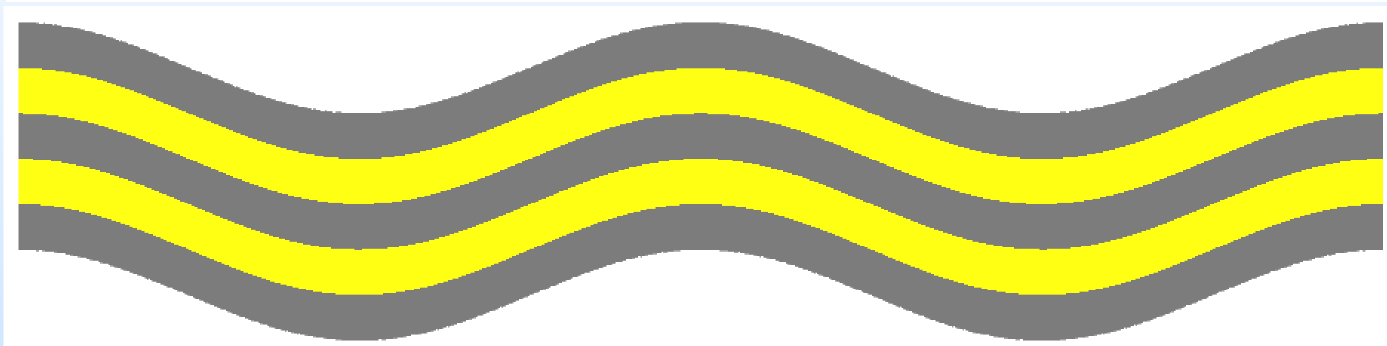
Varying Anticline Amplitude

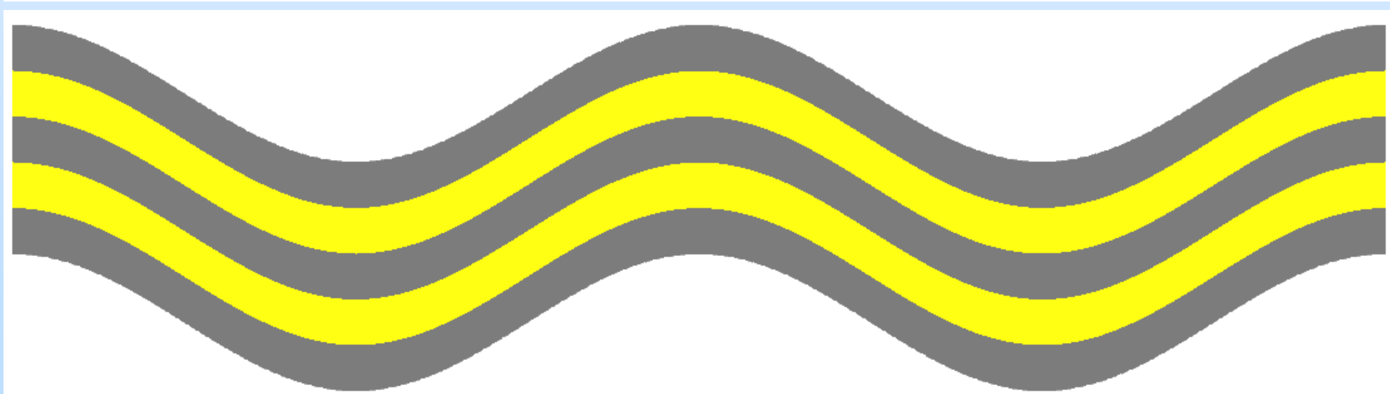
50 m



100 m



150 m



Far-Field Stress Regimes

- Extensional Regime:
  - Uniaxial strain assumption used to calculate horizontal stress
- Strike-slip Regime:
  - $\sigma_H=1.2\sigma_v$, $\sigma_h=0.8\sigma_v$
- Compressional Regime:
  - $\sigma_H=1.5\sigma_v$, $\sigma_h=1.25\sigma_v$

Pre-Injection Critical Pore Pressure

- Maximum allowable pore pressure based on Mohr Coulomb Failure model
- At failure:

$$\sigma_1 - P_p = 2C_o \frac{\cos\ \phi}{1 - \sin\phi} + \frac{1 + \sin\phi}{1 - \sin\phi}(\sigma_3 - P_p)$$

- $P_{crit,intact}$:

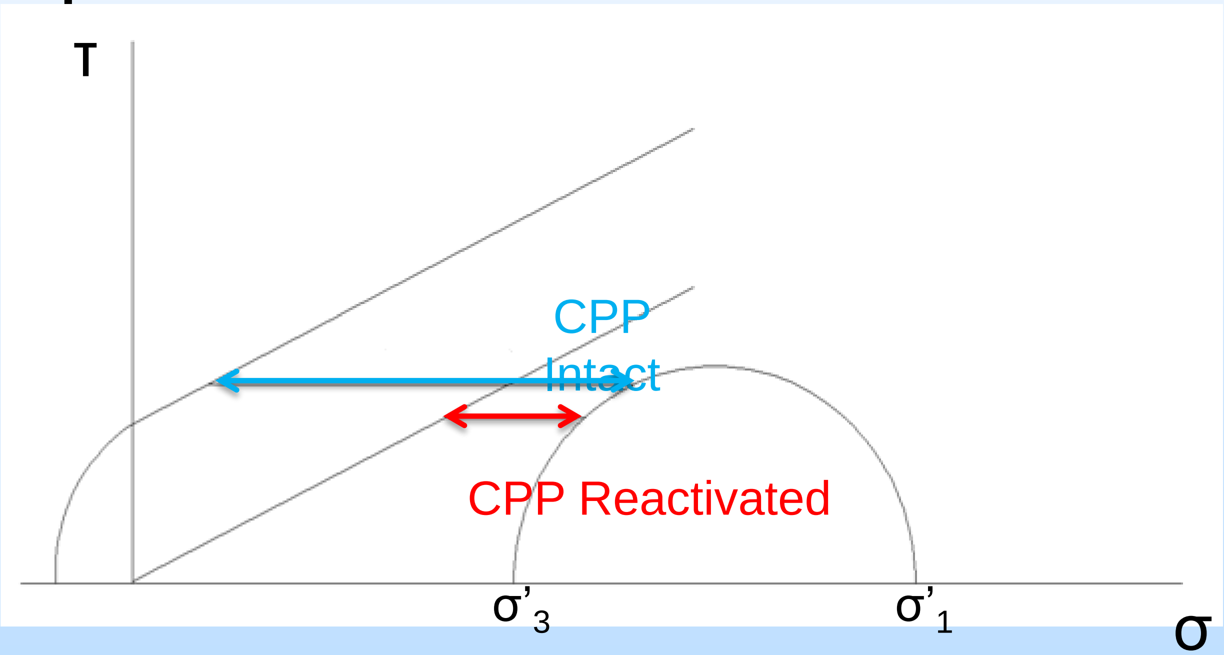
$$P_{cr,intact} = S_o \frac{\cos\phi}{1 - \sin\phi} + \frac{3\sigma_3 - \sigma_1}{2}$$

- $P_{crit,reactivated}$:

$$P_{cr,react\ shear} = \frac{3\sigma_3 - \sigma_1}{2}$$

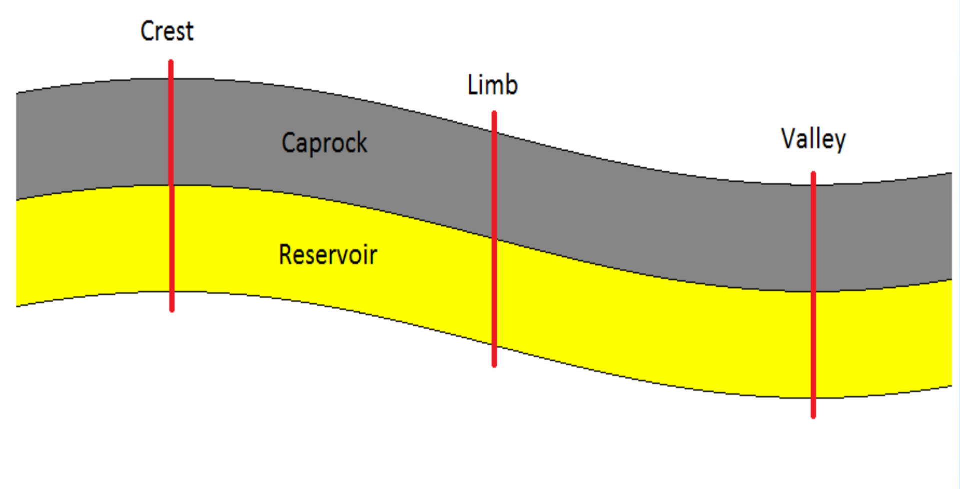
Graphically Representing CPP

- Shortest distance along the normal stress axis from the Mohr circle to the failure envelope



Results

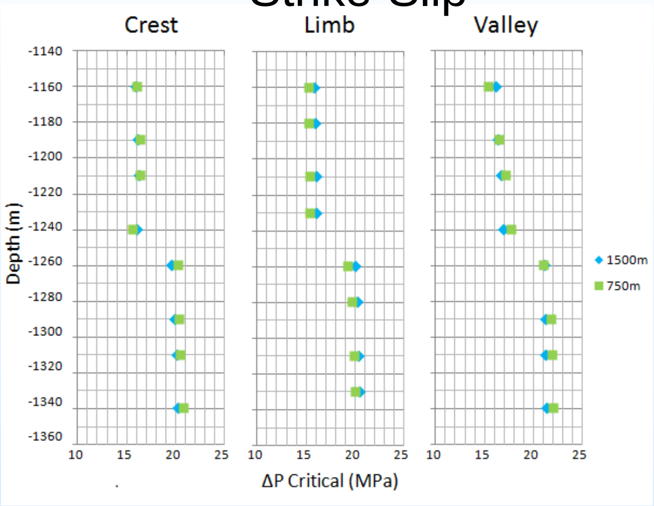
- Results were plotted at three locations in the anticline; crest, limb, and valley
- In general the crest of the formation is most likely to have reactivation of fractures



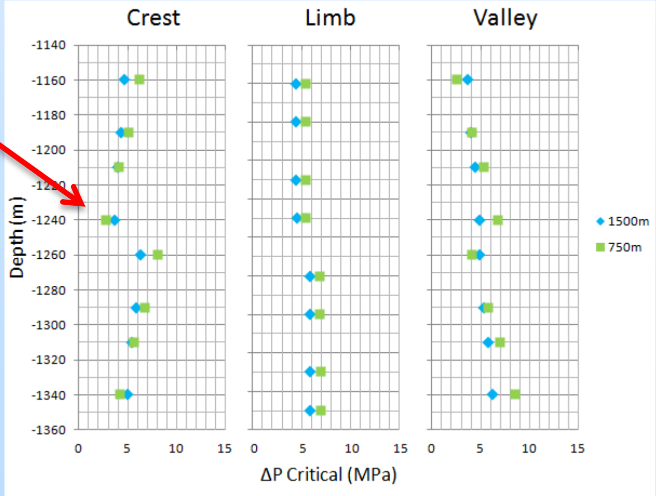
CPP vs Anticline Wavelength

- Lowest values for CPP at crest for all stress regimes
- Shorter wavelength has slightly higher CPP overall
  - Lowest value is 2.5 MPa

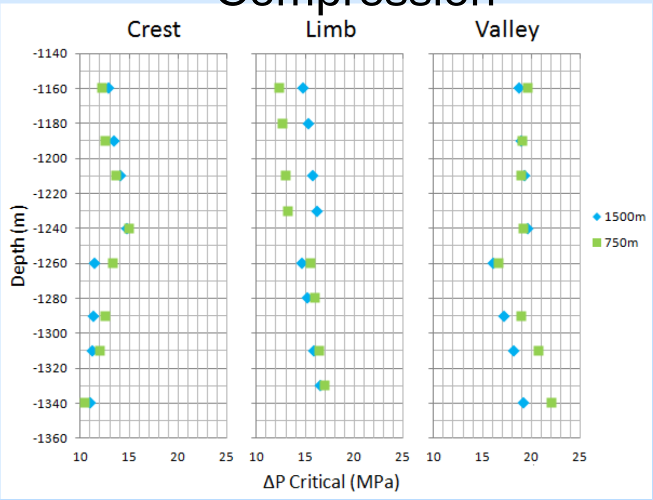
Strike-Slip



Extension



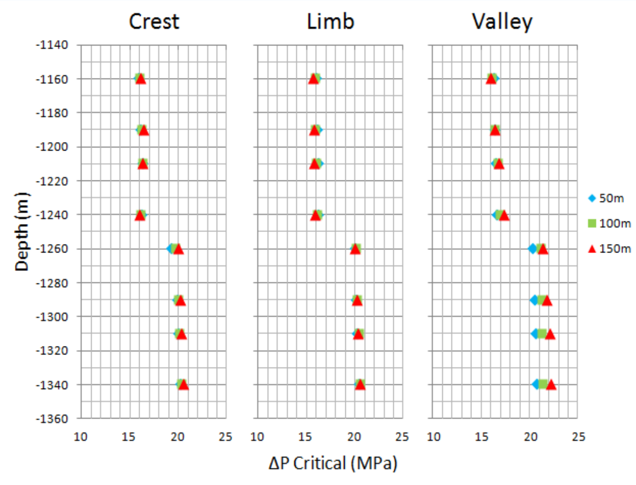
Compression



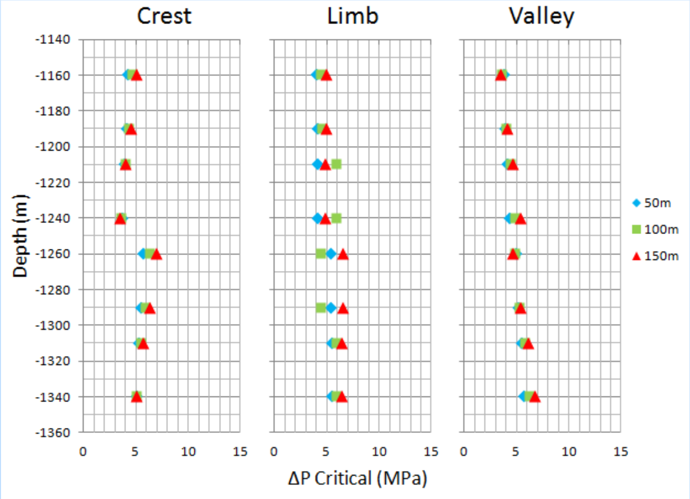
CPP vs Anticline Amplitude

- Crest is the most vulnerable
- Differences are most notable in strike-slip and compression regimes
- The larger amplitude tends to exhibit larger CPP

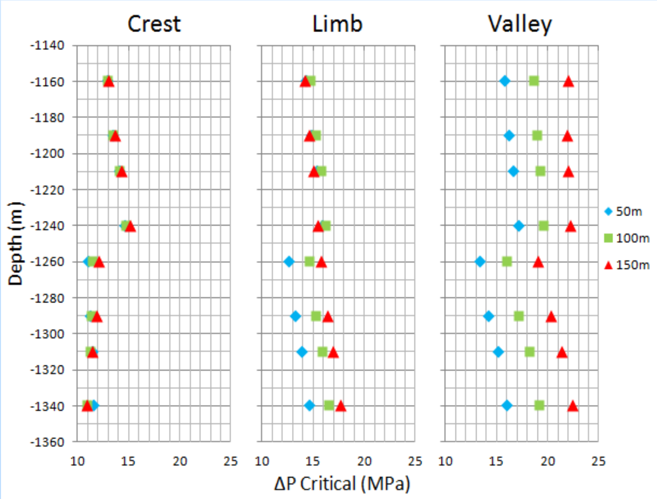
Strike-Slip



Extension



Compression



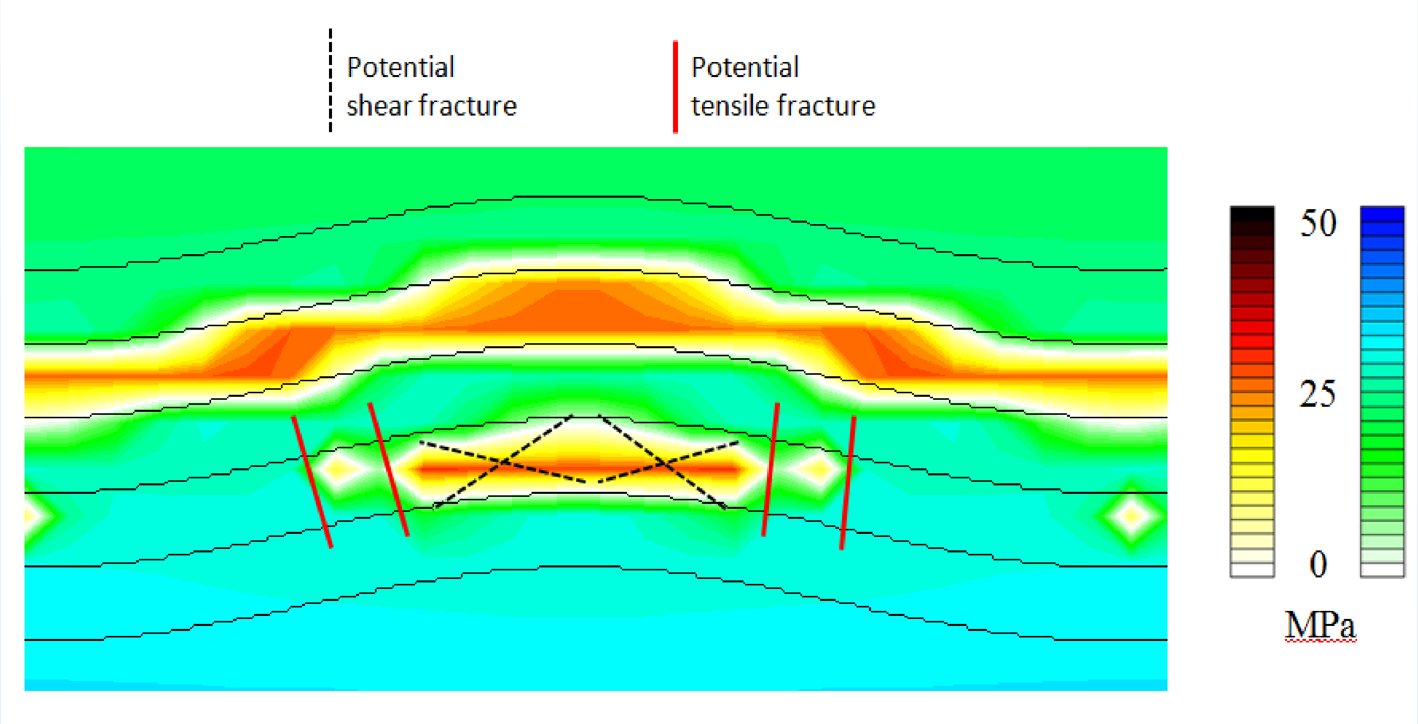
Necessity of 3D Models

- Analytical solutions are available that predict the CPP based on known far-field stresses
- The addition of complex geometry invalidates those solutions

$\Delta P_{crit,r}$ (MPa) for various stress regimes			
	Extension	Strike-slip	Compression
Analytical solution for horizontally layered basin	0	6.7	24.0
Numerical anticline model	5.9	11.4	13.1

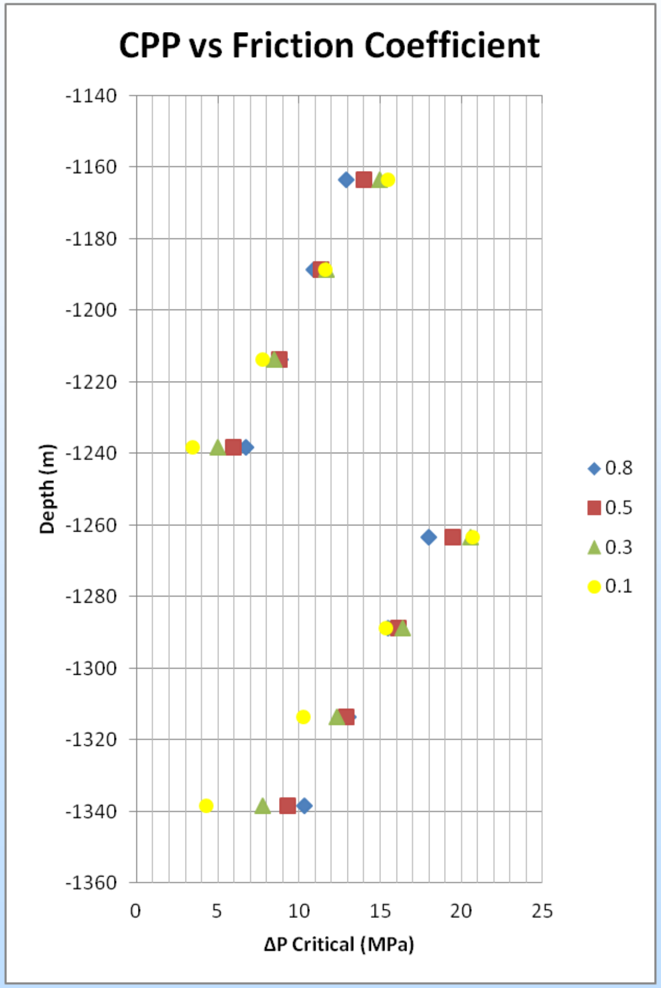
Locations and type of fractures

- Shear fractures would be developed in the crest of the structure
- Tensile failure likely in the limbs



CPP vs Friction between layers

- Lower COF has higher heterogeneity in each layer
- Lowest COF shows biggest difference between reservoir and cap rock
- Lowest value is 4 MPa in the 0.1 COF case



Conclusions

- Three dimensional models are required when the geometry is complex
- Shorter wavelength sustains higher pore pressure
- For reactivation of shear fractures, the strike-slip regimes has the highest CPP
- Relevance of geometric parameters is different for each stress regime

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

Role of Geometrical Influences of CO_2 Sequestration in Anticlines

Andreas Eckert, Amin Amirlatifi, Runar Nygaard

Abstract

This paper presents a thorough parametric modeling study of generic anticline structures and investigates the influence of layer thickness, wavelength and amplitudes at different depths and under different boundary conditions on the maximum CO_2 storage amount. A new approach for generating more realistic three dimensional generic models using finite element analysis preprocessors and converting them into finite difference grids for fluid flow simulations under different geometrical and physical conditions is presented.

Introduction

Often numerical CO_2 injection scenarios are based on the simplified assumption of a horizontally layered sedimentary basin. While this scenario serves well to study the impact of different parameters (such as permeability, injection rate, fluid flow boundary conditions and seal efficiency) on CO_2 flow and pressurization, for a geomechanical risk analysis a model geometry reflecting the actual geologic scenario, which exhibits a heterogeneous state of stress is required.

One of the most important geomechanical risks accompanying aquifer pressurization due to the CO_2 injection is the reactivation of existing faults or fracture sets which can result in induced seismicity and potential leakage pathways. The pressure build-up in models representing horizontally layered sedimentary basins is strongly dependent, amongst others, on the fluid flow boundary conditions.

One reason for the utilization of simple geometries for generic fluid flow simulation studies is due to the lack of flexible pre-processors, which can generate finite difference grids of more complex geometries. In this paper we utilize our file convertor to convert more realistic geometries that are generated in Hypermesh® to ABAQUS® format and later to Eclipse® file format.

Modeling Approach

The general layout of the anticline structures used throughout this modeling study comprises seven layers where all layers are assumed to be fully saturated with water. The pseudo 3D model employed here is part of a direct line CO_2 sequestration scheme with a lateral extension of 76 meters where the injection well is placed at the crest of the anticline and two brine production wells are placed at the sides to keep the hydrostatic pressure under open boundary conditions.

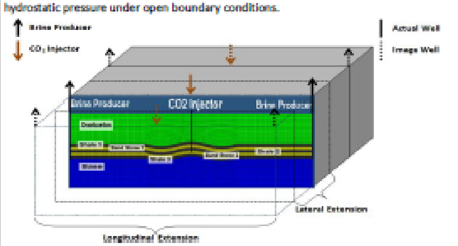


Fig. 1. General layout of the anticline structure used in this study

As a reference base case of this study we consider a reservoir at the depth of 1250 meters with an anticline of a wavelength of 1500 m, an amplitude of 150 m and a height of 100 meters. The injection well is located at the crest of the anticline and the boundaries are assumed to be closed. An initial CO_2 injection rate of 20.7 KTons/year (1798.71 lbs/MWhr) is based on the 50% reinjection of CO_2 emission rate of a common 495 MW capacity coal fired power plant with 75% efficiency over 100 years period and CO_2 density of 1.98 Kg/m³.

Layer Name	ρ (Kg/m³)	E (GPa)	ν	ϕ (%)	k (10^{-15}m²)	h (m)
Overburden	2210	15	0.25	0.01	0.098	950
Shale 1	2130	15	0.25	0.01	0.0009	100
Sand Stone 1	2210	20	0.25	20	986.9	100
Shale 2	2130	15	0.25	0.01	0.0009	100
Sand Stone 2	2210	20	0.25	20	986.9	100
Shale 3	2130	15	0.25	0.01	0.0009	100
Base	2245	15	0.25	0.01	0.098	1050

Table 1. Properties of layers used in the parametric study.

Attribute \ Values	Units							
Wave Length	m	∞	3000	1500	750			
Reservoir Thickness	m	100	50	25				
Amplitude	m	150	100	50				
Boundary Type		Open	Semi-Open	Closed				
Model Size (Longitudinal Extension)	Km	6	23	103				
Depth	m	500	1000	1250	1500	2000	2500	3000
Maximum Allowable Pore Pressure	MPa	26.3	34.1	36.0	41.8	49.5	56.5	62.4
Well Location		Crest						
Injection Rate (STD)	KTons/Year	20.7						

Table 2. Range of parameters used in the parametric study.

Simulation Results

Table 3 shows that the highest storage capacity is observed for the high wavelength of 1500 meters, the low amplitude of 50 meters and the thick reservoir of 100 meters thickness and the height or net thickness of the reservoir has a direct effect on the CO2 storage capacity.

Wavelength (m)	Amplitude (m)	Height (m)	SIL (Years)	Occupancy (%)	Mass of Injected CO_2 KTons
750	50	25	1.81	1.75	32.54
		50	3.71	1.84	68.14
		100	7.23	1.82	134.66
	100	25	1.73	1.67	30.92
		50	3.46	1.73	63.46
		100	6.82	1.74	126.93
1500	50	25	1.9	1.82	33.98
		50	3.79	1.87	69.58
		100	7.32	1.83	136.10
	100	25	1.73	1.68	30.92
		50	3.57	1.76	64.90
		100	6.82	1.72	126.93
	150	25	1.65	1.6	30.56
		50	3.29	1.65	60.95
		100	6.35	1.62	117.58

Table 3. Simultaneous variation of wavelength, amplitude and height.

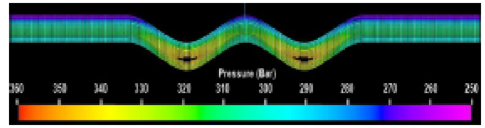


Fig. 2. Pressure distribution in base model after 7 years of injection, showing the failed regions

Table 4 shows the significant influence of the fluid flow boundary conditions. Whilst a closed system (resembling a compartmentalized reservoir) yields a SIL of only 6.35 years and an occupancy of only 1.62%, Open and semi-open systems yield much higher SIL (50-80 years) and much higher occupancies (25-26%).

The semi-open system yields overall safer conditions and more CO_2 can be injected by allowing partial pressure increase in the reservoir, resulting in compression of CO_2 and contained spread of the plume. The contained spreading gives higher sweep efficiency and continuous flow of fluids in the system, which itself results in increased contact between the two fluids and dissolution of CO_2 in the brine.

While open systems benefit from the favorable pressure gradient that makes it possible for CO_2 to quickly spread in the system, mix with the brine as it spreads and dissolve in it, unconstrained spreading of the plume results in lower sweep efficiency than that of the semi-open system.

Boundary Type	SIL (Years)	Occupancy (%)	Average Reservoir Pressure (MPa)	Mass of Injected CO_2 KTons
Closed	6.35	1.62	32.4	117.58
Open	50	25.13	13.1	942.10
Semi- Open	80	25.96	20.4	1506.65

Table 4. Effect of Boundary Conditions on CO_2 Storage Capacity of the base case.

Table 5 shows that CO_2 sequestration in deep formations results in longer safe CO_2 injection periods and consequently higher CO_2 storage capacity. The highest occupancy is observed in 2500 meters depth with a value of 2.13% and the deepest model at a depth of 3000 meters has the longest injection period of 9.78 years.

Comparison between the increase in injection period and the increase in depth and the occupancy suggests that 2500 meters is the most favorable depth of all cases under closed boundary conditions.

Reservoir Depth (m)	Maximum Allowable Pore Pressure (MPa)	SIL (Years)	Occupancy (%)	Mass of Injected CO_2 KTons
500	26.3	5.266	1.57	97.45
1000	34.1	6.28	1.60	116.41
1250	36.0	6.35	1.62	117.58
1500	41.8	7.73	1.88	143.86
2000	49.5	8.877	2.04	165.52
2500	56.5	9.619	2.13	179.44
3000	62.4	9.78	2.10	182.53

Table 5. Effect of Depth variation on CO2 Storage Limit.

Simulation Results (Cont'd)

Table 6 shows that although the occupancy of the two models in a closed system is the same, the thinner reservoir of 50 meter thickness shows a better sweep and occupancy of 28.95% under the open conditions, compared to the 25.13% of the 100 meter thick reservoir. While the difference in the volume of the two reservoirs controls the mass of injected CO_2 and SIL, the difference in occupancy can show the influence of geometrical parameters that may be masked out otherwise by the influence of the fluid flow boundary conditions.

Height (m)	Boundary Type	SIL (Years)	Occupancy (%)	Average Reservoir Pressure (MPa)	Mass of Injected CO_2 KTons
50	Closed	3.29	1.62	32.5	60.95
	Open	30.72	28.95	13.9	577.13
100	Closed	6.35	1.62	32.4	117.58
	Open	50	25.13	13.1	942.10

Table 6. Effect of reservoir height and boundary condition variation on CO2 storage capacity

Results presented in table 7 show that the lateral fluid flow boundary conditions have a significant influence on CO2 sequestration parameters. Although huge aquifers such as Sleipner exist through out the world that have high potential for CO2 sequestration, they may not be in the vicinity of the power plant(s) of interest or meet the salinity level requirements set forward by federal or state regulations; thus an important step in CO2 sequestration feasibility study of a candidate aquifer should be determination of its size.

Reservoir Size (Km)	Reservoir Volume (10^6 m³)	SIL (Years)	Boundary Type	Mass of Injected CO_2 KTons
6	9.13	6.35	Closed	117.58
6	9.13	50	Open	942.11
23	35.0	22.46	Closed	420.71
103	156.7	50	Closed	942.10

Table 7. Comparison of Model Sizes and Boundary Conditions.

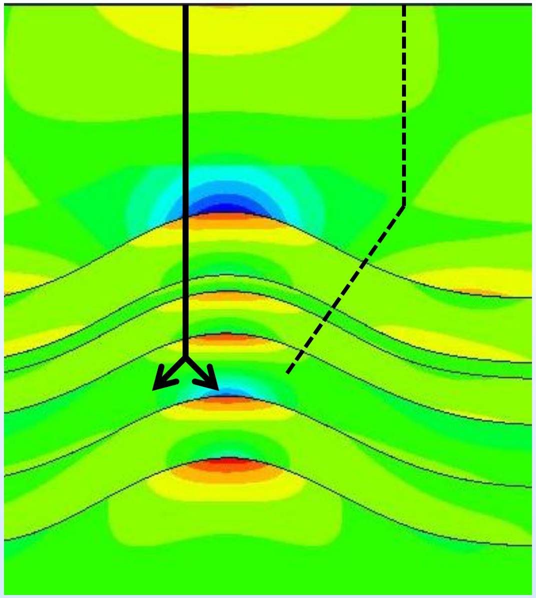
Conclusions

- While the assumption of using horizontally layered basins for CO_2 sequestration studies may be valid for most cases, the need for an actual trap system requires a more realistic geometry for parametric studies and simulations. The geometry should be flexible enough to include faults or fractures and any unconformities that may exist.
- Finite element analysis pre-processors can be used to generate geometries that resemble structural trap systems and successfully convert them into native fluid flow simulation formats. This novel approach enables us to study the influence of geometric parameters such as anticline wavelength, amplitude and thickness.
- Higher wavelengths, lower amplitudes and relatively thick layers provide the best conditions for safe CO_2 sequestration. The depth of the sequestration site also plays an important role.
- For aquifer depths of 2500m and 3000m (for a closed system) the maximum occupancy and SIL can be obtained respectively. If the economic costs of drilling to the deeper aquifers and compression of CO_2 for injection into such reservoirs can be justified, deep CO_2 sequestration results in higher storage capacity.
- A major and not surprising conclusion is that the lateral fluid flow boundary condition of an aquifer system has the most significant influence on the CO_2 sequestration parameters. The assumption of an open system requires gigantic aquifers (~100 km) that may be very difficult, if not impossible, to locate in the vicinity of many CO_2 producers.
- The open system assumption might also lead to over-simplified cases, unless brine production wells are included. A more realistic approach of semi-open fluid flow boundaries yields similar if not better results than the open system case.

Acknowledgment

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

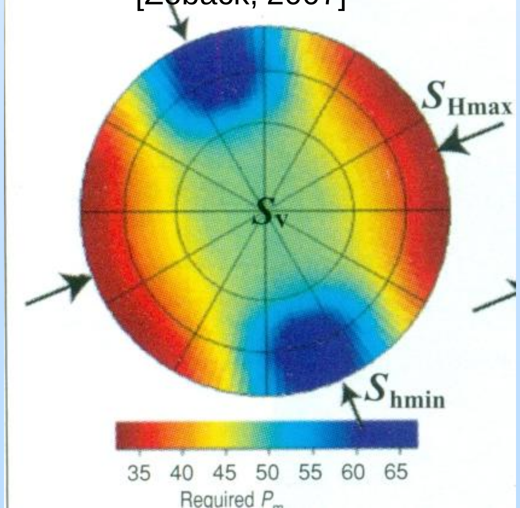
Wellbore stability: objectives



- Wellbore trajectory optimization → in progress
  - Find safe mud weight window
- Optimal wellbore design
  - Sensitivity study on modeling parameters after CO_2 injection → in progress

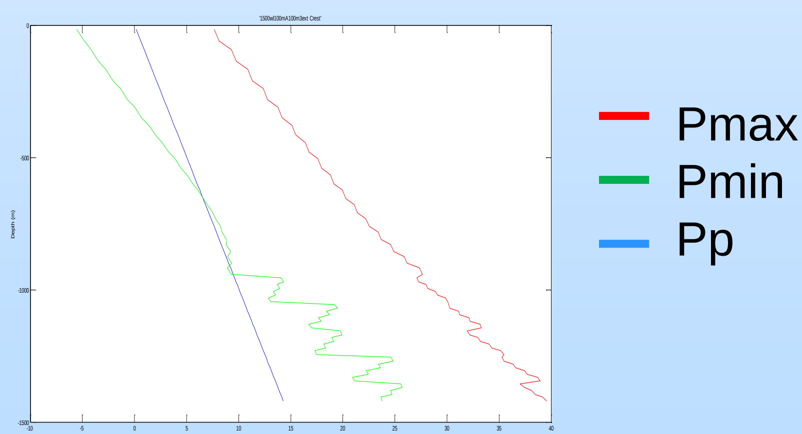
Wellbore trajectory optimization

- Conventional wellbore trajectory planning:
  - Use Andersonian stresses (S_V, S_H, S_h)
  - Determine safe mud weight window for inclined wells

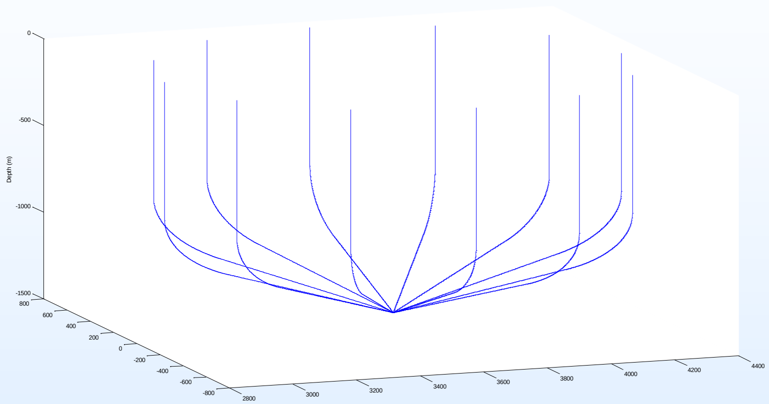


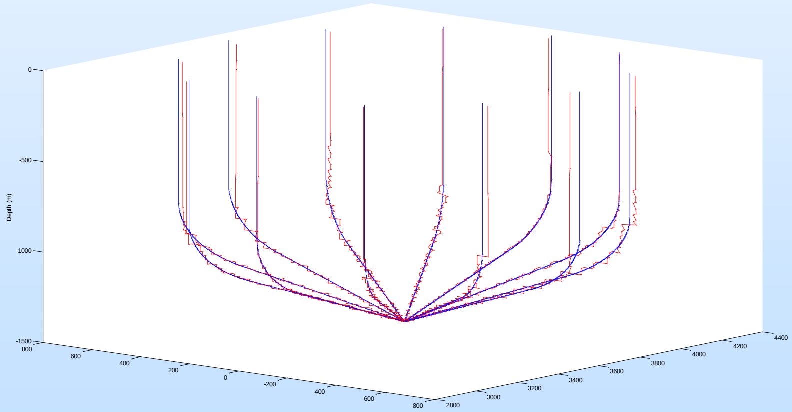
[Zoback, 2007]

- Advantage of numerical approach:
  - Full stress tensor used as input
  - Not limited to Andersonian state of stress
  - Implementation of full virtual well path



Wellbore trajectory planning

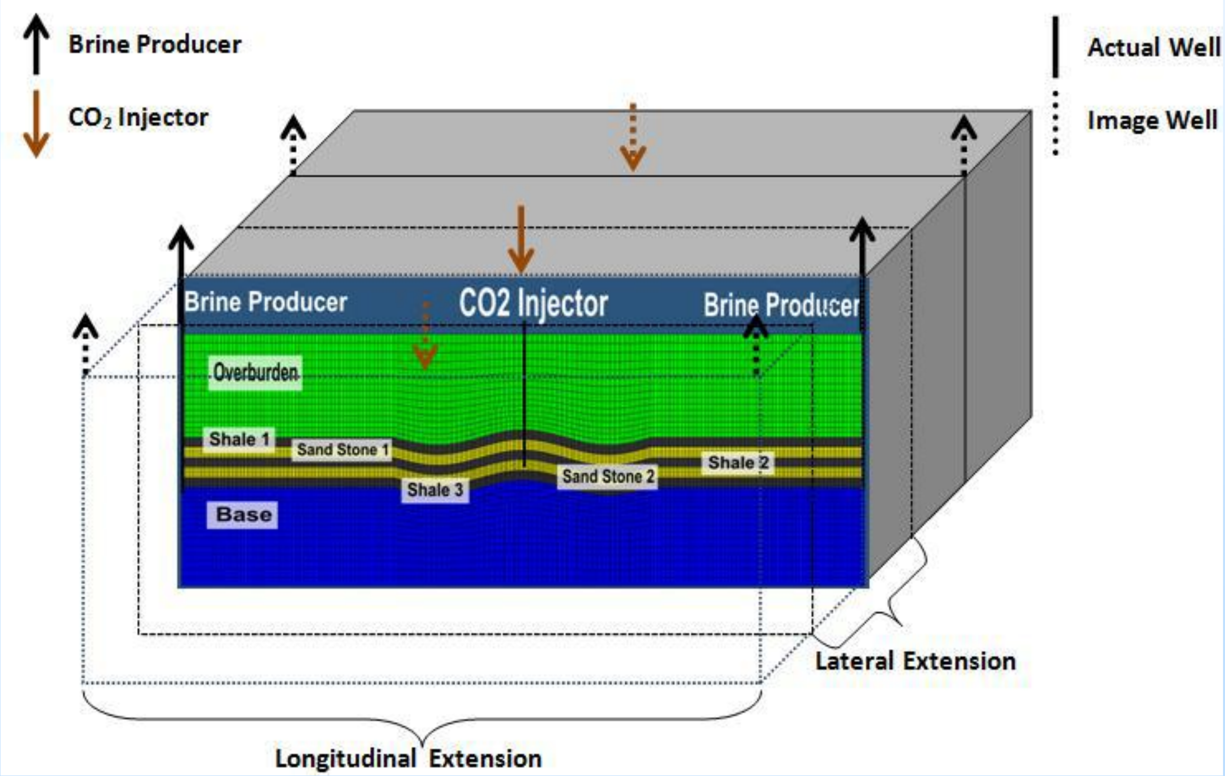




- Calculate type I inclined well paths
  - Vertical section, inclined section, inclination angle
- Extract stress results from FE model locations
- Calculate mud weight window (for all cases from the 3D reservoir scale model)
- Results analysis in progress

Coupled model

- Coupling module developed in Project DE-FE0001132
- Run simulations: in progress



Accomplishments to Date

- 4 Graduate students (3 MSc, 1PhD) trained in numerical modeling of CO_2 sequestration applications.
- Pre-injection geomechanical risk assessment (calculation of maximum reservoir pressure) for generic anticline settings completed.
- Detailed sensitivity analysis on stress regime, anticline geometry, inter-bedding friction completed.
- Numerical model parameter optimization of wellbore scale model completed.
- Optimal wellbore placement and trajectory planning for wellbore stability analysis completed.
- CO_2 injection simulation: Detailed sensitivity analysis on flow boundary conditions and anticline geometry completed.

Summary

– Geologic setting (geometry) strongly affects state of stress and associated geomechanical risks. Models should not be simplified to horizontally layered basin.
– Prevailing stress regime and inter-bedding friction important input parameters for FEM models.
– Fluid flow boundary conditions: crucial parameter
– Lessons Learned
– Future Plans

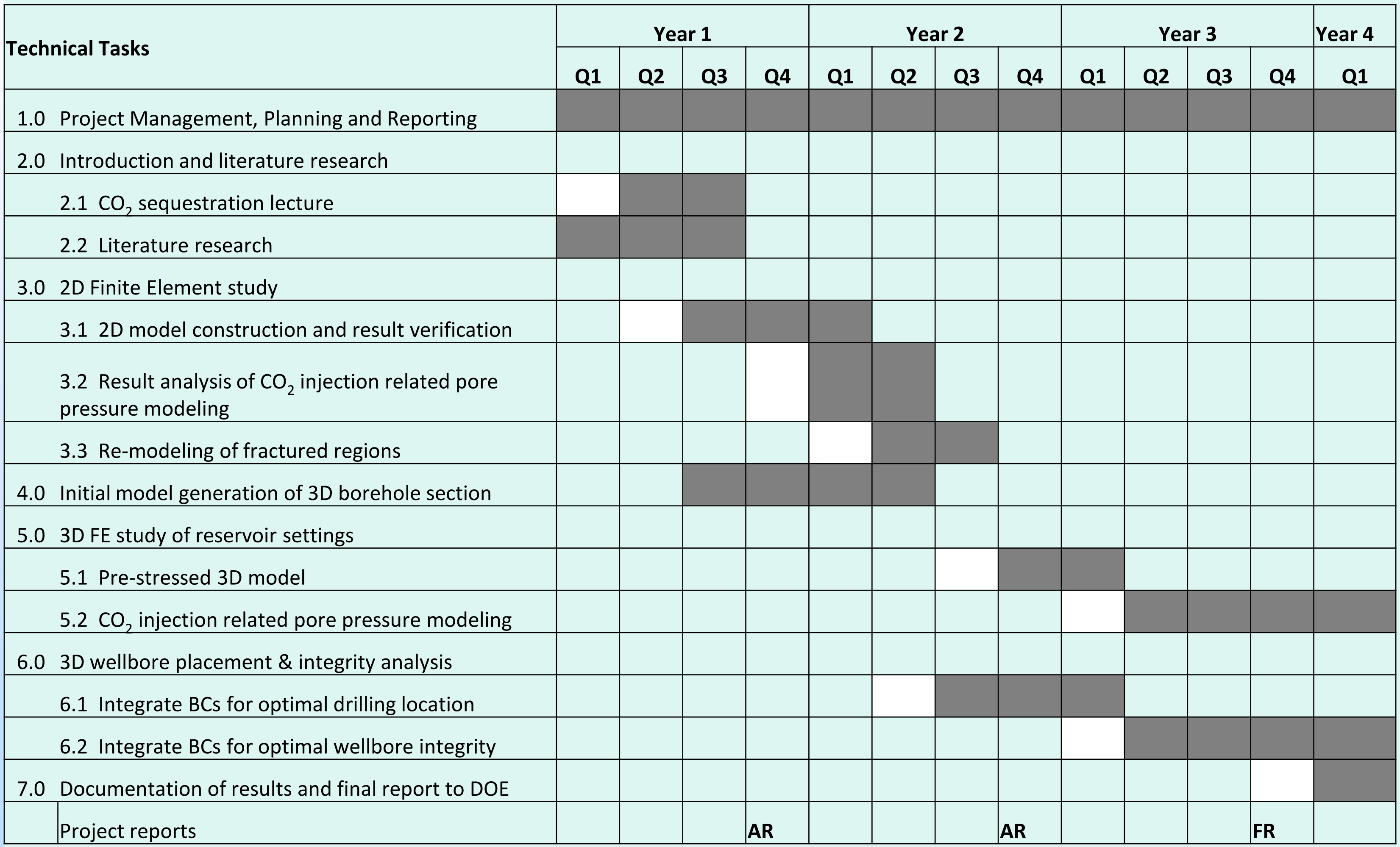
Organization Chart: Project team

- PIs: Dr. Andreas Eckert; Dr. Runar Nygaard
- Graduate students
  - MingYen Lee: MSc student; Petroleum Engineering; graduated;
  - Matthew Paradeis: MSc student; Petroleum Engineering; graduated;
  - Nevan Himmelberg: MSc student; Petroleum Engineering;
  - Amin Amirlatifi: PhD student; Petroleum Engineering;

Project Participants

- Dr. Andreas Eckert: PI
- Dr. Runar Nygaard: Co-PI
- MingYen Lee (ML): PhD student; Petroleum Engineering
- Matthew Paradeis (MP): Masters student; PE
- Nevan Himmelberg (NH): Undergraduate assistant

Gantt chart



AR: Annual report; FR: Final report

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