Enhanced Analytical Simulation Tool for CO_2 Storage Capacity Estimation and Uncertainty Quantification

DE-FE0009301

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration

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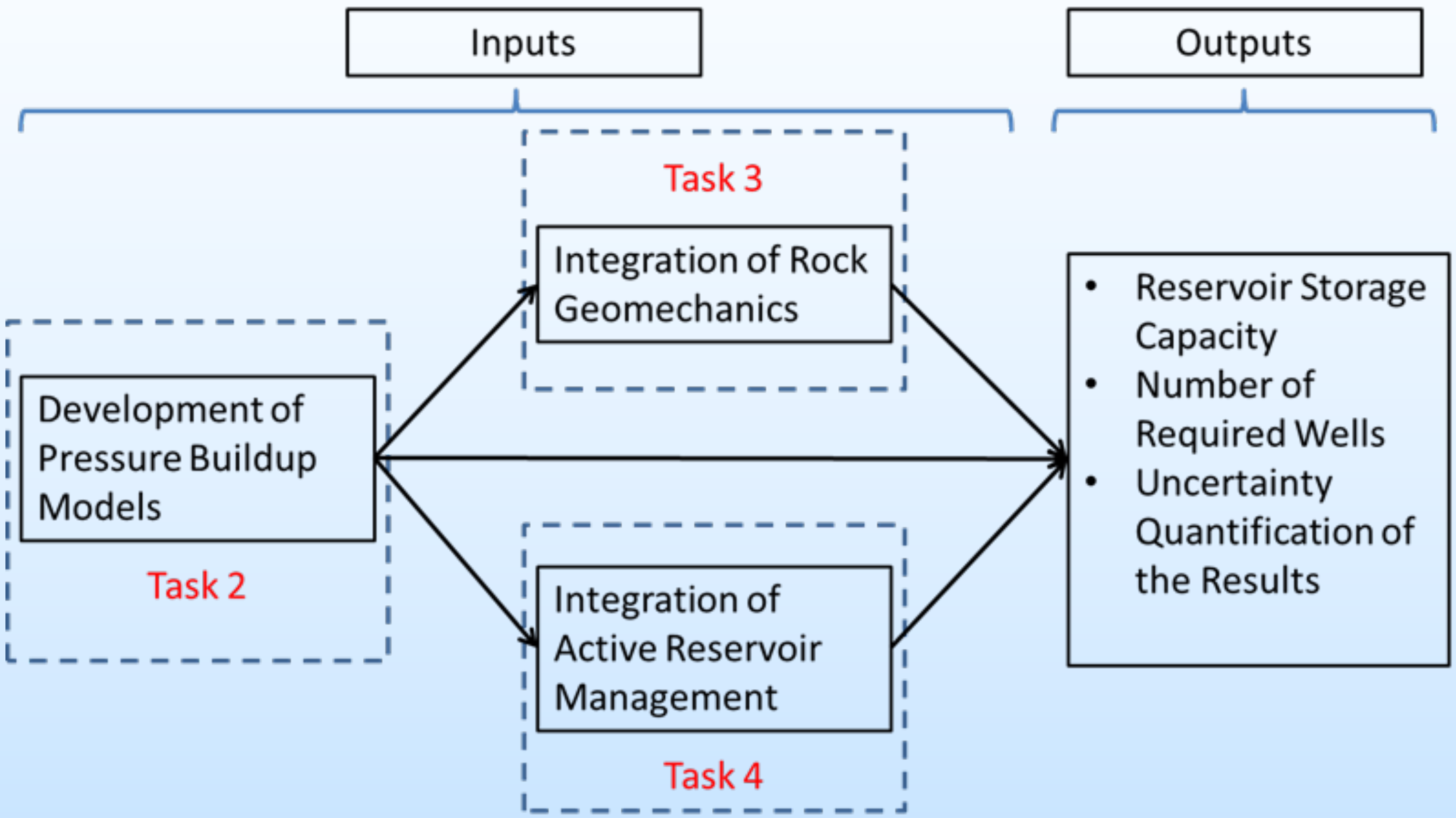
Benefit to the Program/Goals and Objectives

- Project benefit
  - Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Major goal
  - Develop an **Enhanced Analytical Simulation Tool (EASiTool)** for simplified reservoir models to predict storage capacity of brine formations.
- Objectives
  - Provide fast, reliable and science-based estimate of storage capacity
  - Integrate analytical/semi-analytical models
  - Provide uncertainty analysis
  - Implement models into an easy to use interface (MATLAB)

Project Overview

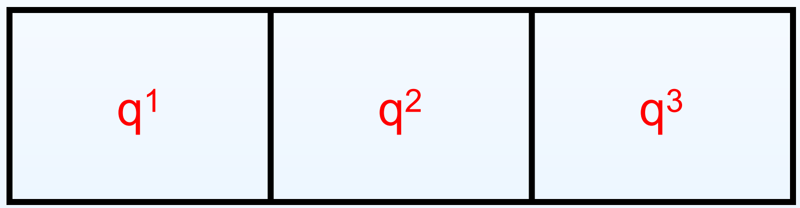
- Task 2&3 completed.
- Task 4 ongoing.



Project start date: 5/1/2013

Accomplishments to Date-1

- Finding the optimized rate to maximize storage capacity



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

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

Accomplishments to Date-2

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

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

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

Accomplishments to Date-3

- Normal fault system

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

- Reverse fault system

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

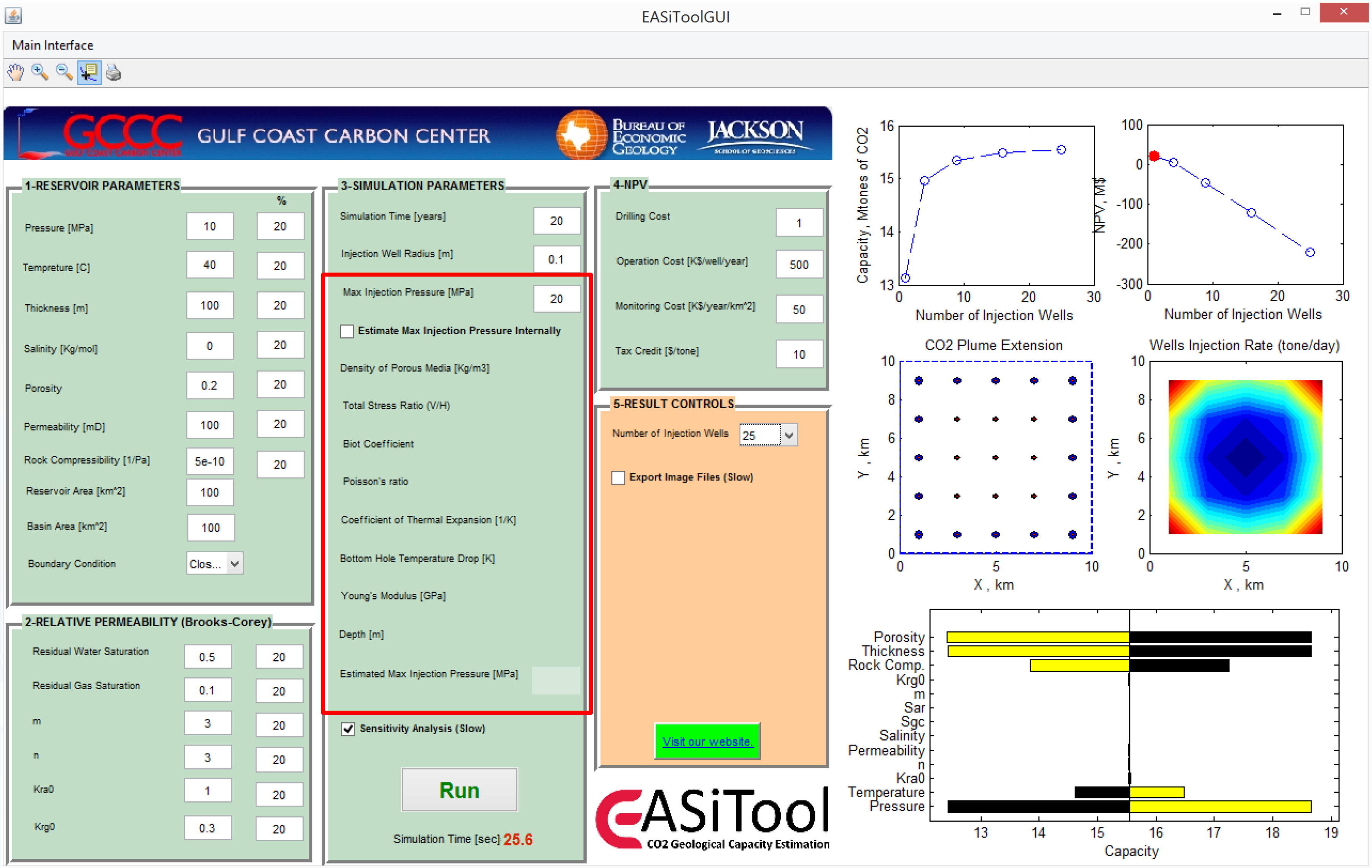
- Strike-slip fault system

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

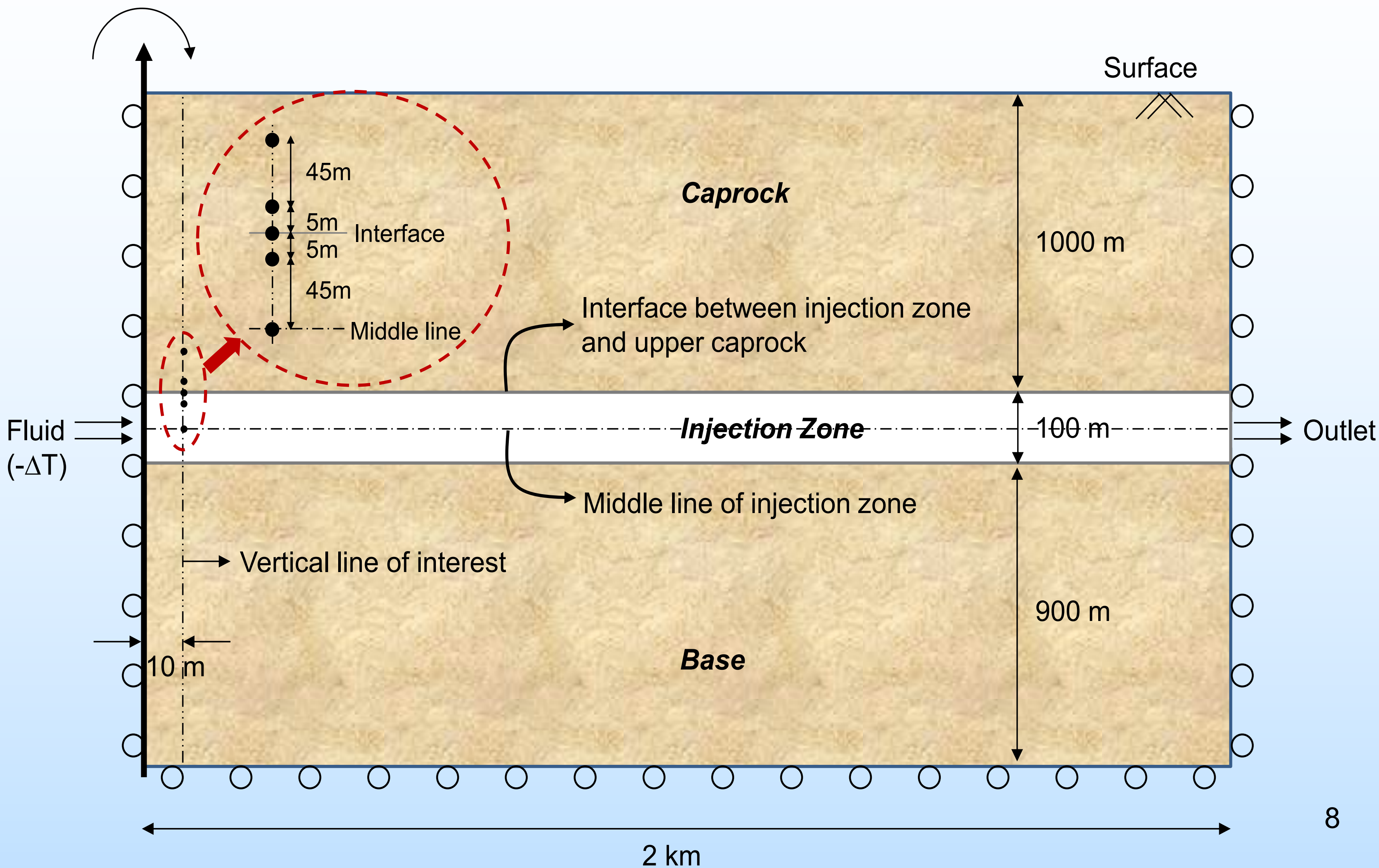
α is Biot coefficient, θ is angle between the pre-existing fracture and minor principal stress, $\mu=\tan\varphi$ is the coefficient of friction, $K=\sigma_{h0}/\sigma_{v0}$ is the initial ratio of total horizontal stress to total vertical stress, $\sigma_{v0}=\int(\rho_{sat}\cdot g)$ is the initial total vertical stress, P_{pi} is initial fluid pore pressure, α_T is the coefficient of thermal expansion, E is Young's modulus, ΔT is thermal drop, and ν is Poisson's ratio and c =0 for cohesion.

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

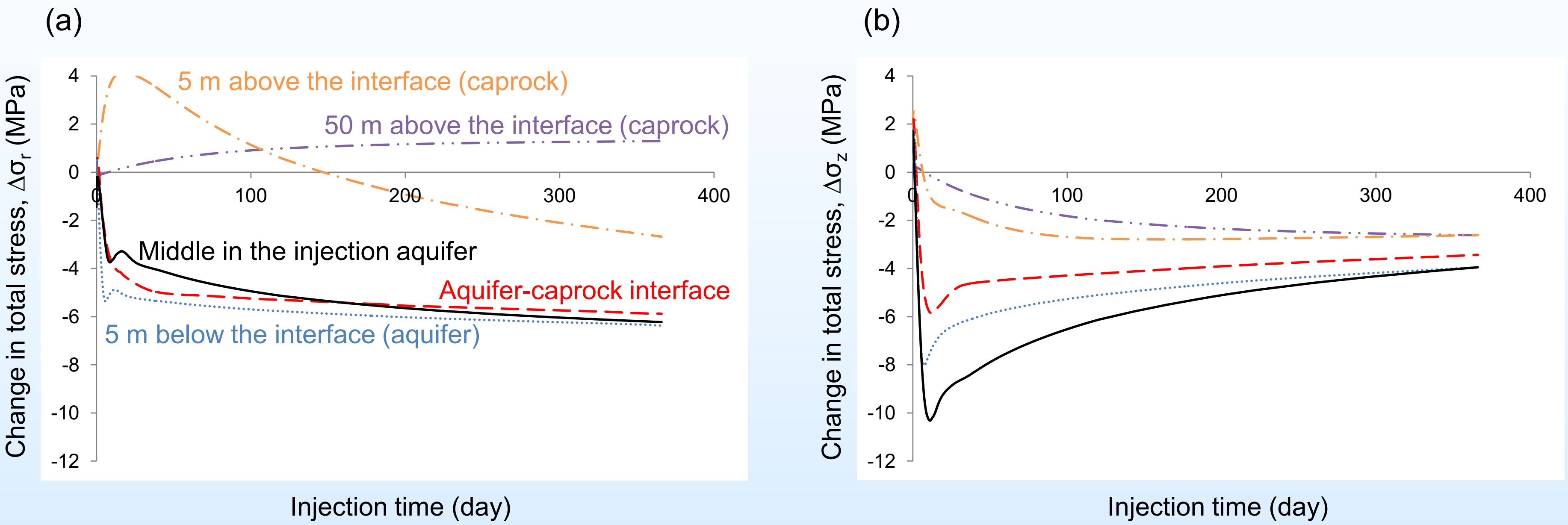
Accomplishments to Date-4



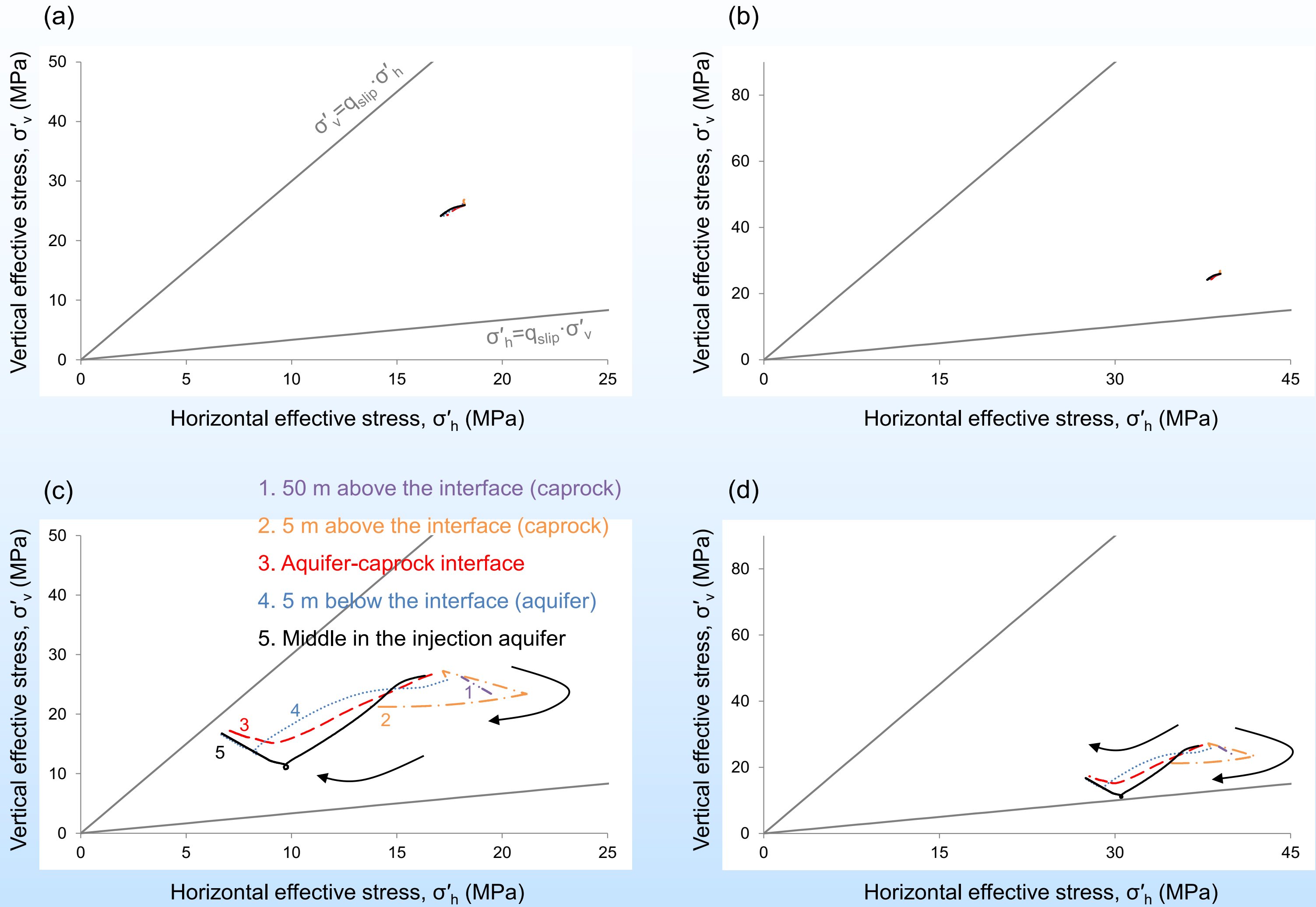
Accomplishments to Date-5



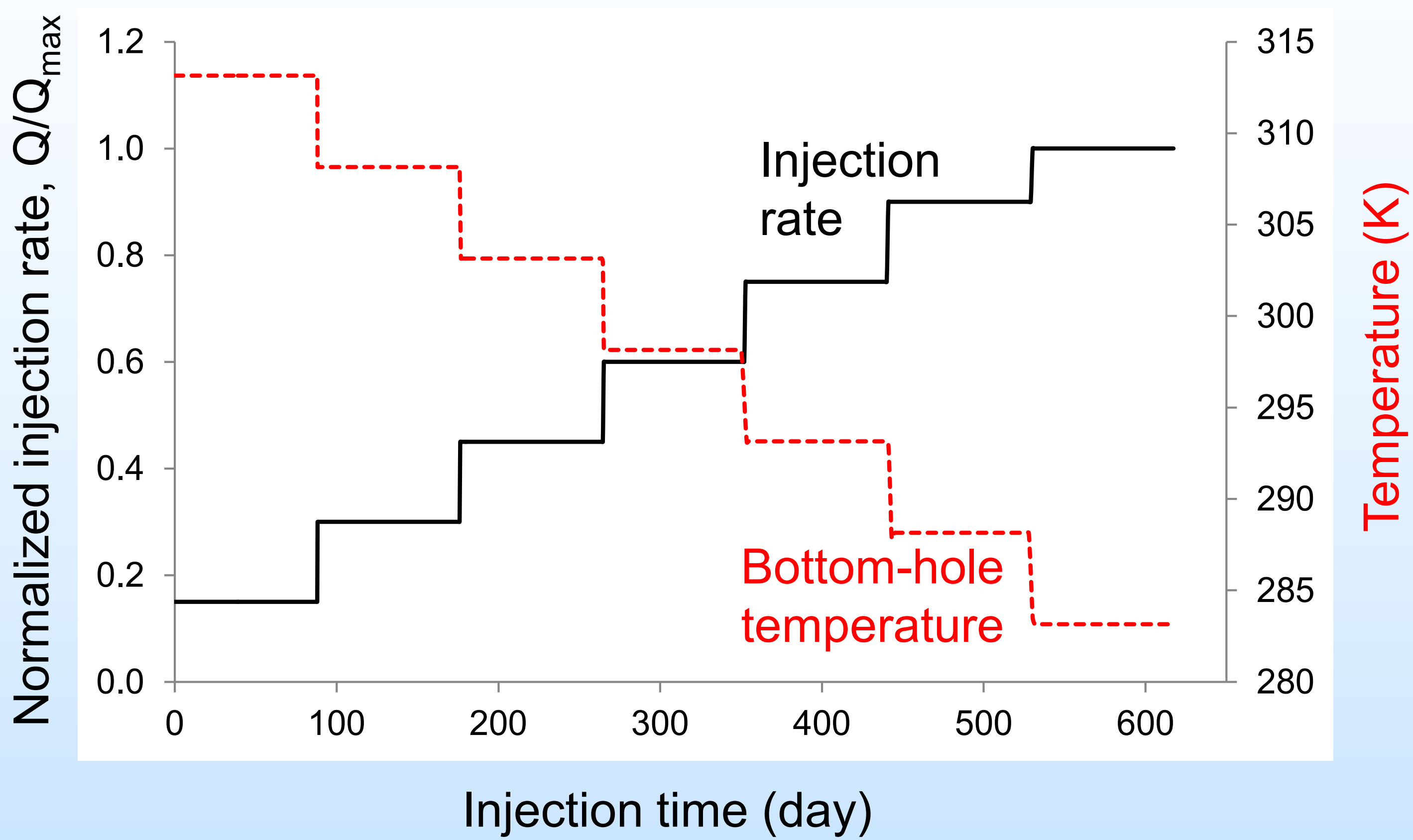
Accomplishments to Date-6



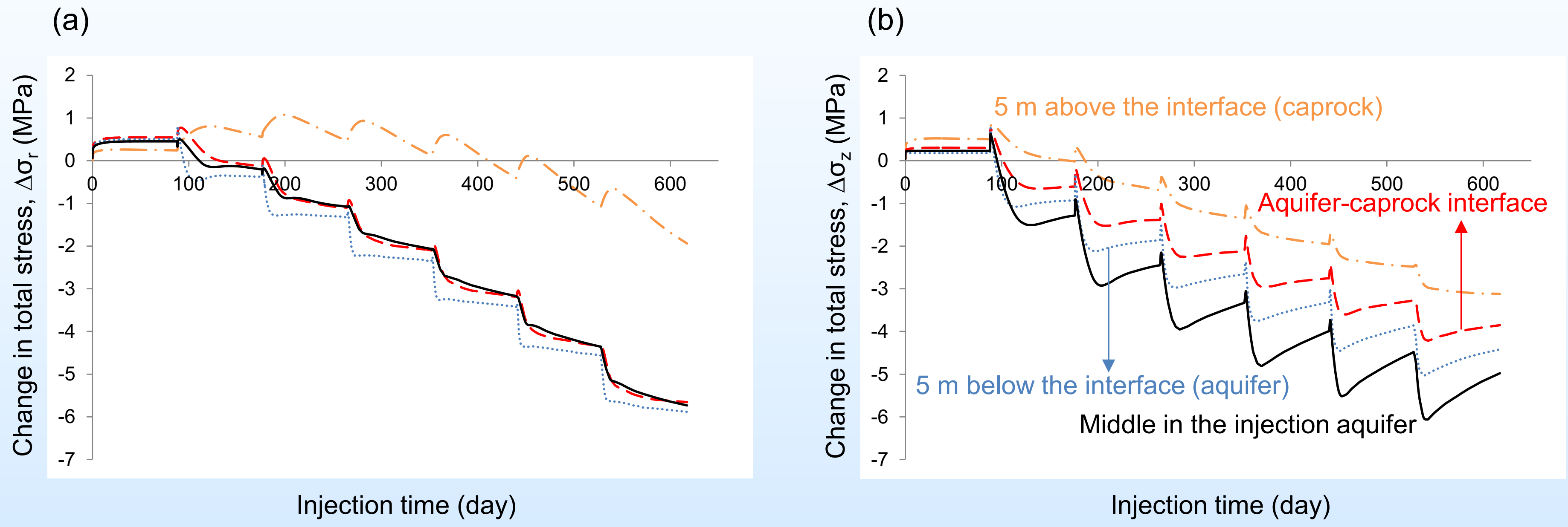
Accomplishments to Date-7



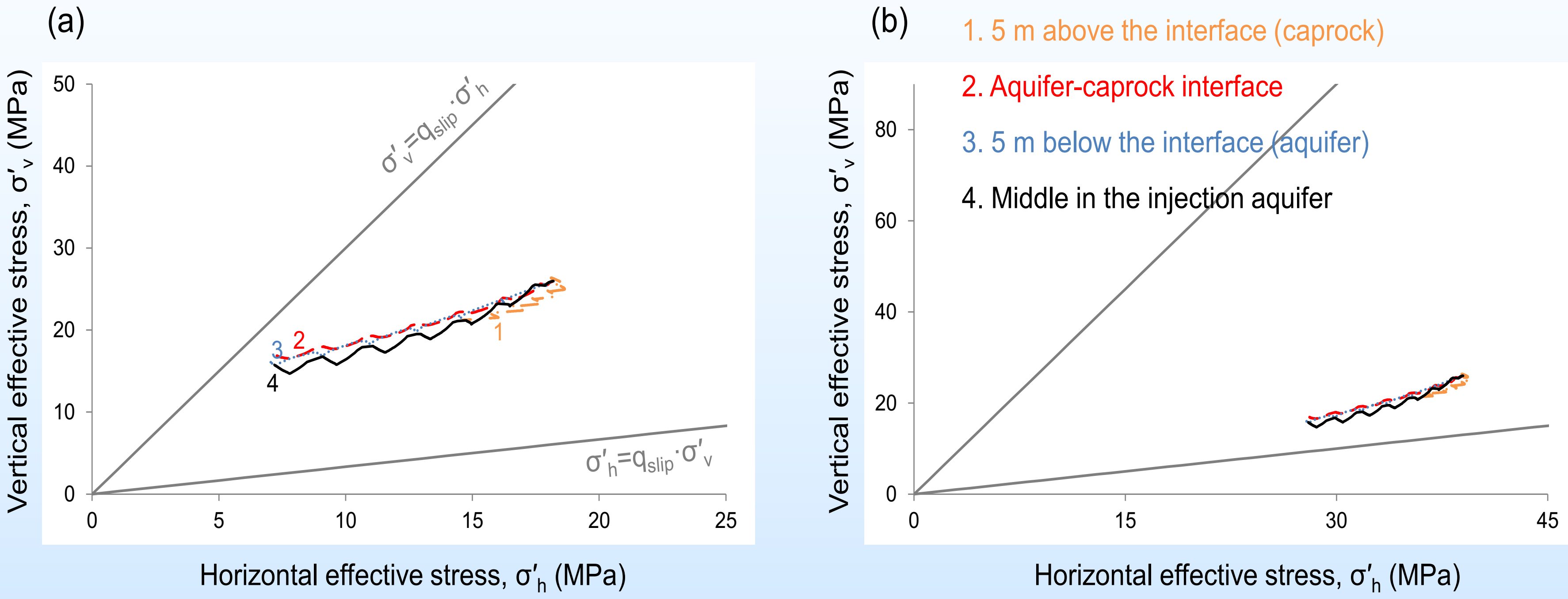
Accomplishments to Date-8



Accomplishments to Date-9



Accomplishments to Date-10

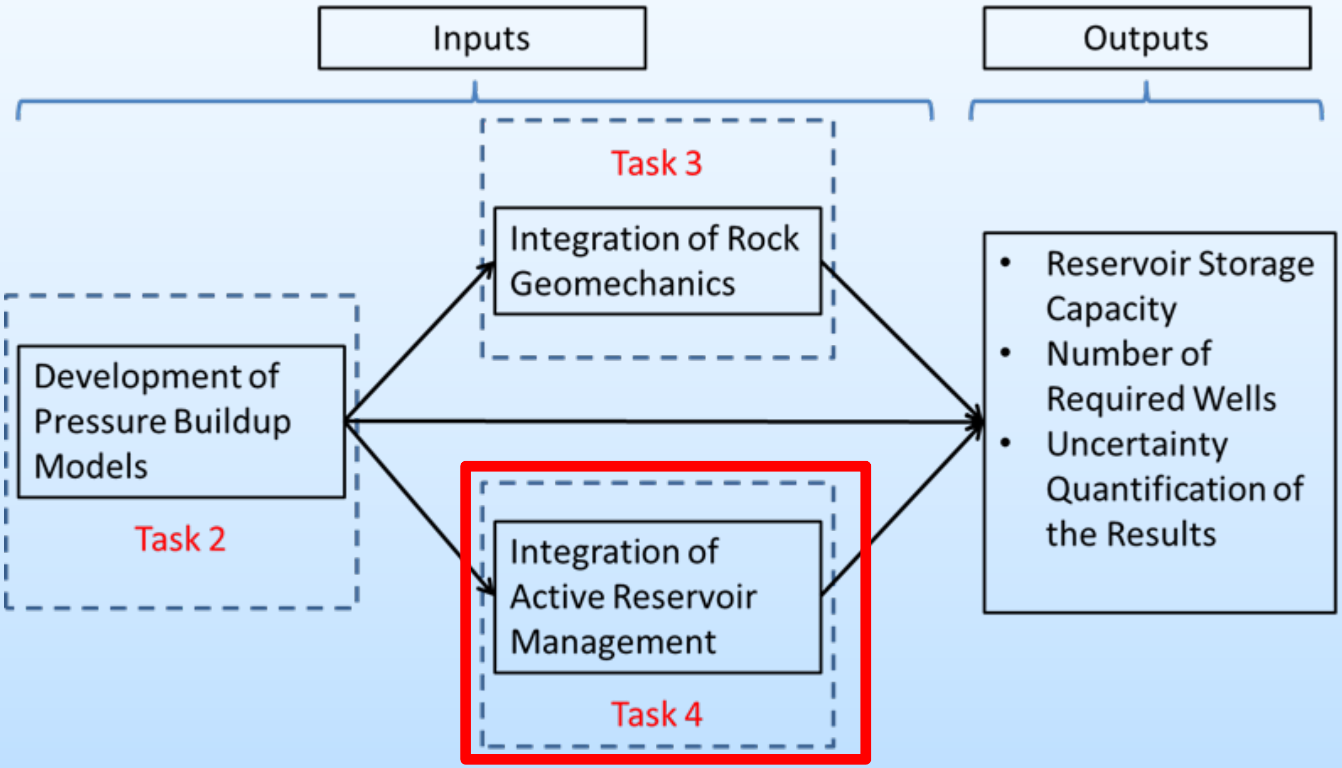


Summary

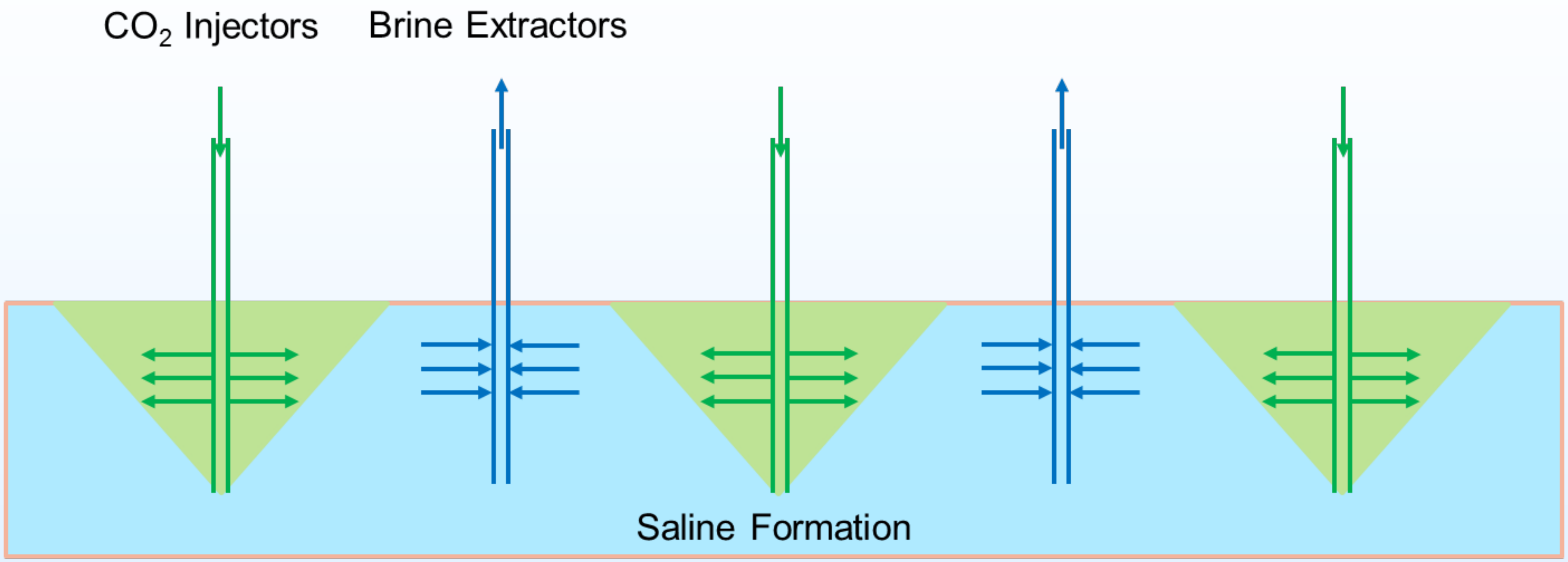
- Second version of EASiTool released on 4/30/2015.
- Geo-mechanical calculations for maximum injection pressure added to EASiTool.
- Geomechanical model integrates thermal and pore pressure stresses.
- EASiTool interface and code updated to include latest developments (MATLAB).
- EASiTool is available for download:
  - http://www.beg.utexas.edu/gccc/EASiTool/

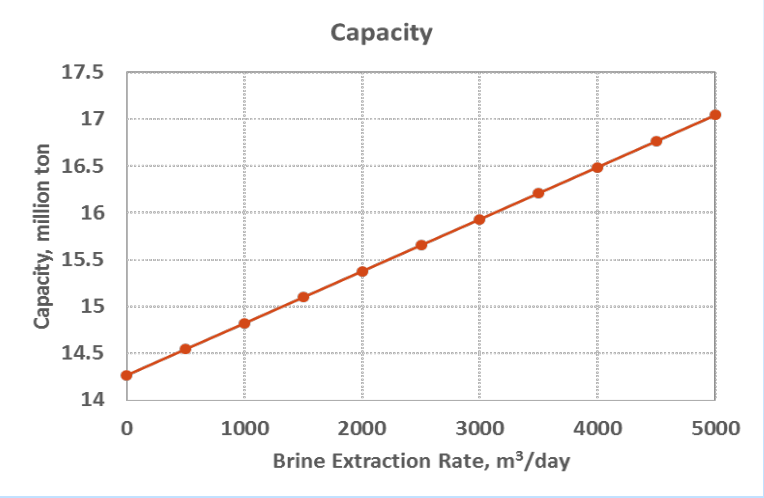
Future Plans

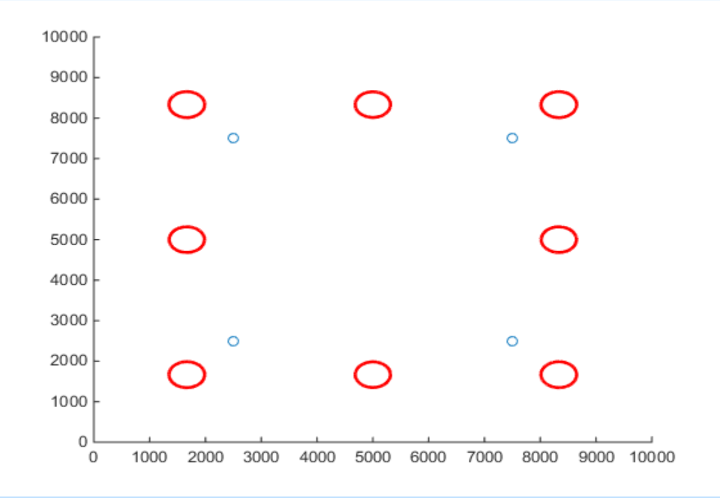
- Currently under Task 4 the main focus is to integrate extraction wells.
  - ❑ Model development
  - ❑ Model verification
- EASiTool Interface development



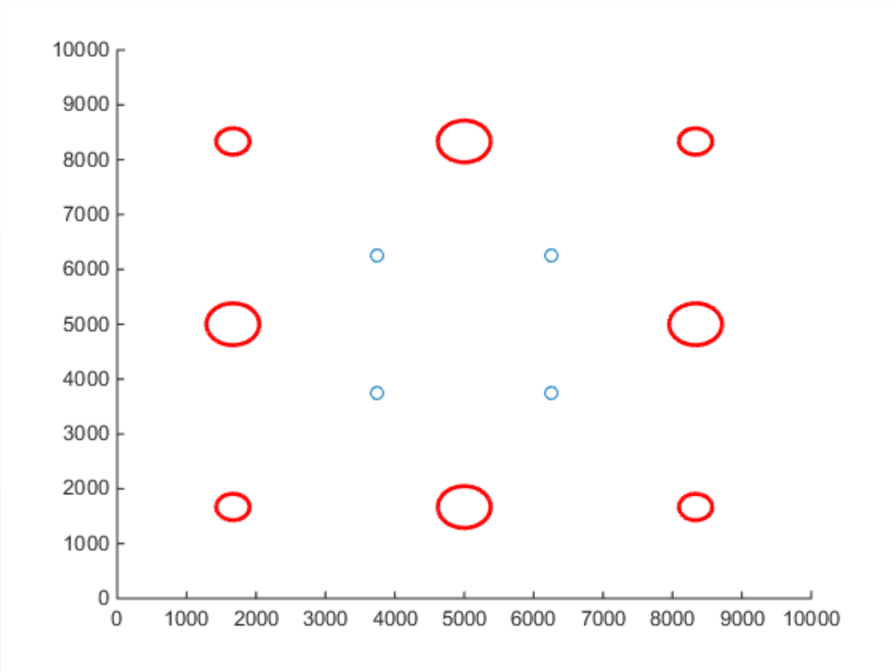
Future plans

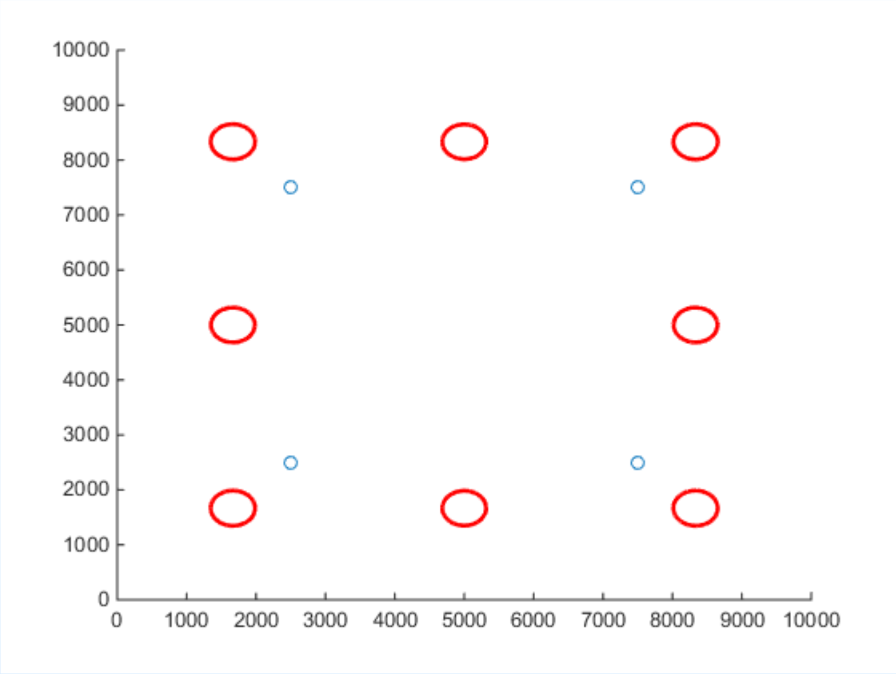






Future plans





Effect of Placement of Extraction Wells on Storage Capacity

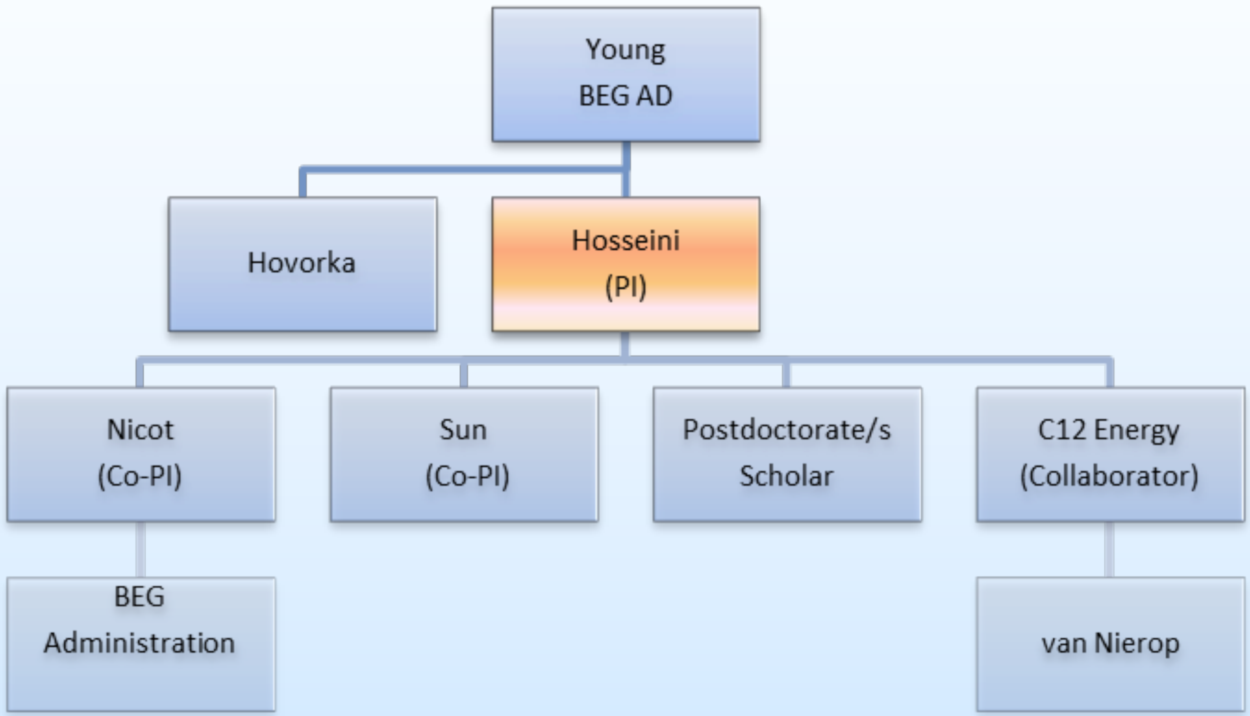
END

» Questions/Comments

Appendix

– Organization Chart
– Gantt Chart
– Bibliography
– Extra Slides

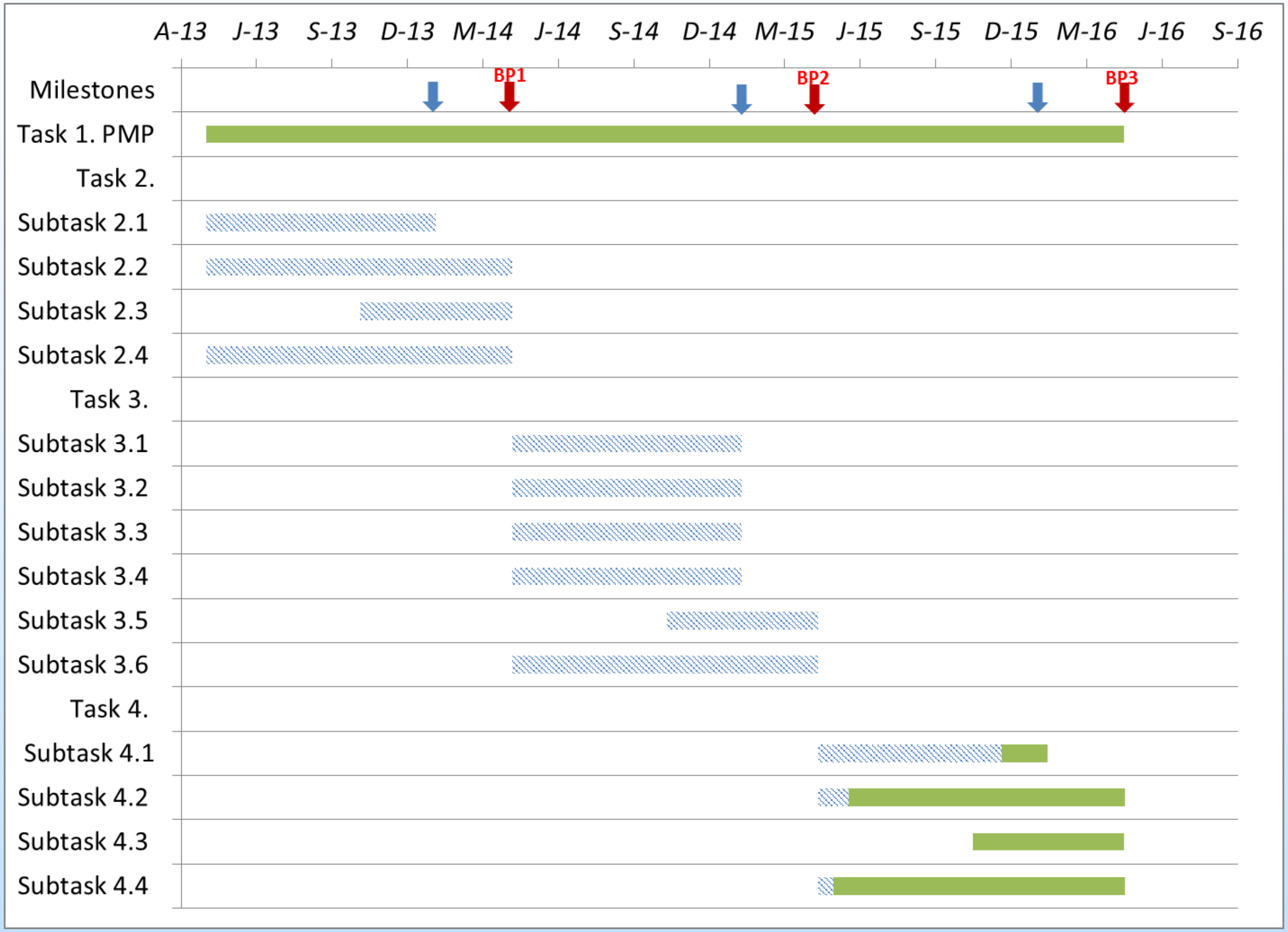
Organization Chart



Organization Chart

Project PI: Seyyed A. Hosseini			
Task 1 Project Management and Planning	**Task 2** Development of Analytical Solutions for Pressure Buildup	**Task 3** Rock Geomechanics Impact on Pressure Buildup and Capacity Estimation	**Task 4** Brine-Management Impact on CO_2 Injectivity and Storage Capacity
Task Leader/Backup Nicot/Hosseini	Task Leader/Backup Hosseini/Sun	Task Leader/Backup Hosseini/Sun	Task Leader/Backup Hosseini/Sun
Task 1 Team Nicot/Hosseini/ Young/Hovorka	Task 2 Team Subtask 2.1 Hosseini/Sun/ Postdoc/s Subtask 2.2 Hosseini/Sun/C12 Energy Subtask 2.3 Sun/Hosseini Subtask 2.4 Sun/Hosseini	Task 3 Team Subtask 3.1 Hosseini/Sun/ Postdoc/s Subtask 3.2 Hosseini/Sun/ Postdoc/s Subtask 3.3 Sun/Hosseini Subtask 3.4 Hosseini/Sun Subtask 3.5 Sun/Hosseini Subtask 3.6 Sun/Hosseini	Task 4 Team Subtask 4.1 Hosseini/Sun/ Postdoc/s Subtask 4.2 Sun/Hosseini/ Postdoc/s Subtask 4.3 Sun/Hosseini Subtask 4.4 Sun/Hosseini

Gantt Chart



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M-16
J-16
S-16
Milestones
BP1
BP2
BP3
Task 1. PMP
Task 2.
Subtask 2.1
Subtask 2.2
Subtask 2.3
Subtask 2.4
Task 3.
Subtask 3.1
Subtask 3.2
Subtask 3.3
Subtask 3.4
Subtask 3.5
Subtask 3.6
Task 4.
Subtask 4.1
Subtask 4.2
Subtask 4.3
Subtask 4.4

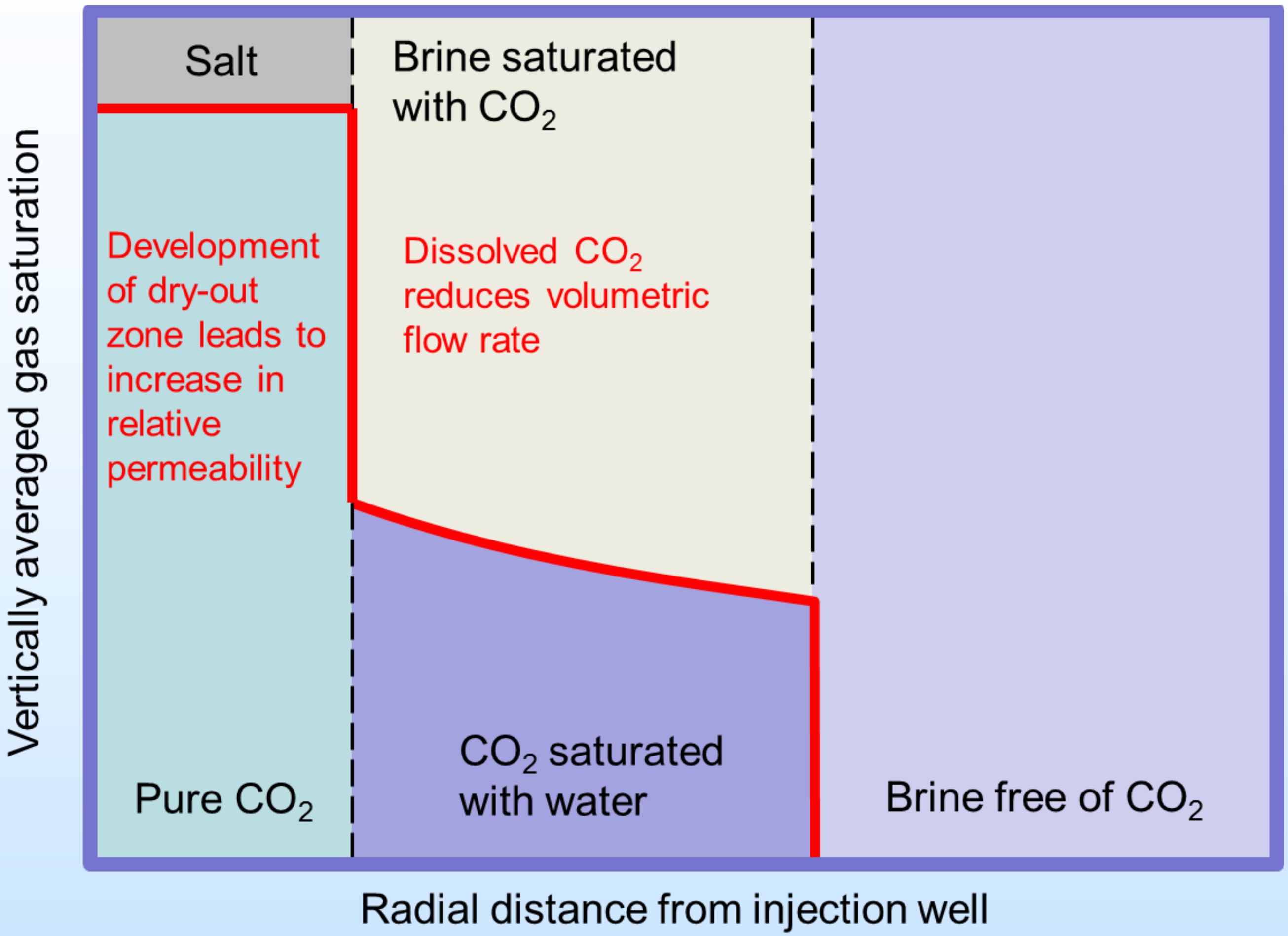
Bibliography

- Journals
  - Kim, S., Hosseini, S.A, 2013, Above-zone pressure monitoring and geomechanical analyses for a field-scale CO_2 injection project in Cranfield, MS, Greenhouse Gases: Science and Technology, 4 (1), 81-98, DOI: 10.1002/ghg.1388
- Conferences
  - Kim, Seunghee, Hosseini, S. A., and Hovorka, S. D., 2013, Numerical Simulation: Field Scale Fluid Injection to a Porous Layer in relevance to CO_2 Geological Storage: Proceedings of the 2013 COMSOL Conference, Boston, Massachusetts.
  - Kim, Seunghee, Hosseini, S. A., 2014, Optimization of Injection Rates for Geological CO_2 Storage in Brine Formations, 13th Annual Conference on Carbon Capture Utilization & Storage.
  - Kim, Seunghee, Hosseini, S. A., 2014, Effect of Pore Pressure/Stress Coupling on Geological CO_2 Storage, 13th Annual Conference on Carbon Capture Utilization & Storage.

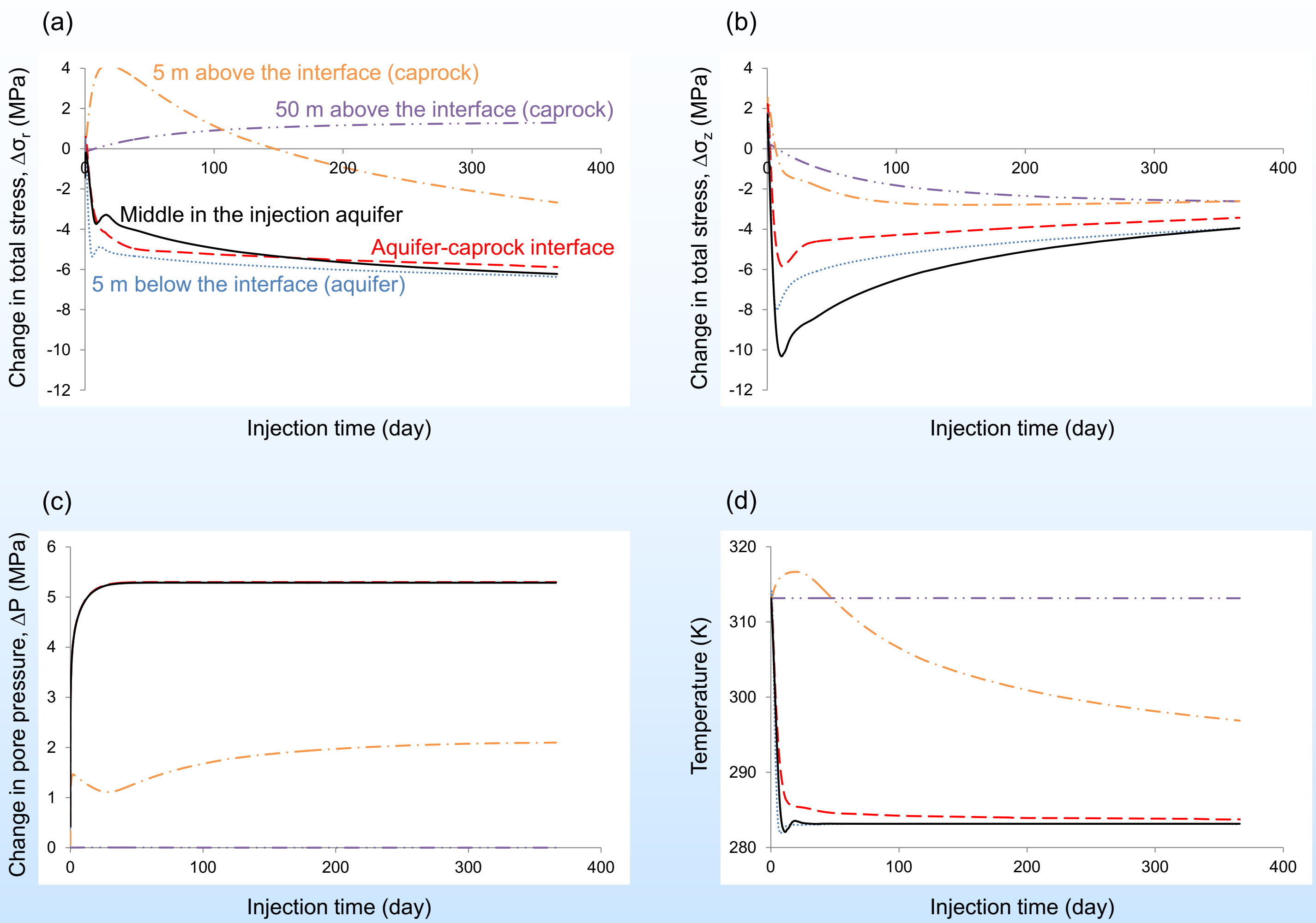
Capacity Estimation Methods

Tool/Approach Name	DOE/NETL	EERC	CSLF	USGS	EASiTool	Numerical Simulators
Reservoir scale	Yes	Yes	Yes	Yes	Yes	Yes
Accuracy	Low	Medium	Low	Low	Medium/High	High
Boundary conditions	No	No	No	No	Yes	Yes
Rock geomechanics	No	No	No	No	Yes	Yes
Brine management	No	No	No	No	Yes	Yes
Required expertise	Low	Low	Low	Low	Low	High
Cost of use	Low	Low	Low	Low	Low	High
Speed	High	High	High	High	High	Low
Dynamic	No	No	No	No	Yes	Yes
Uncertainty quantification	No	No	No	Simple	Yes	Yes

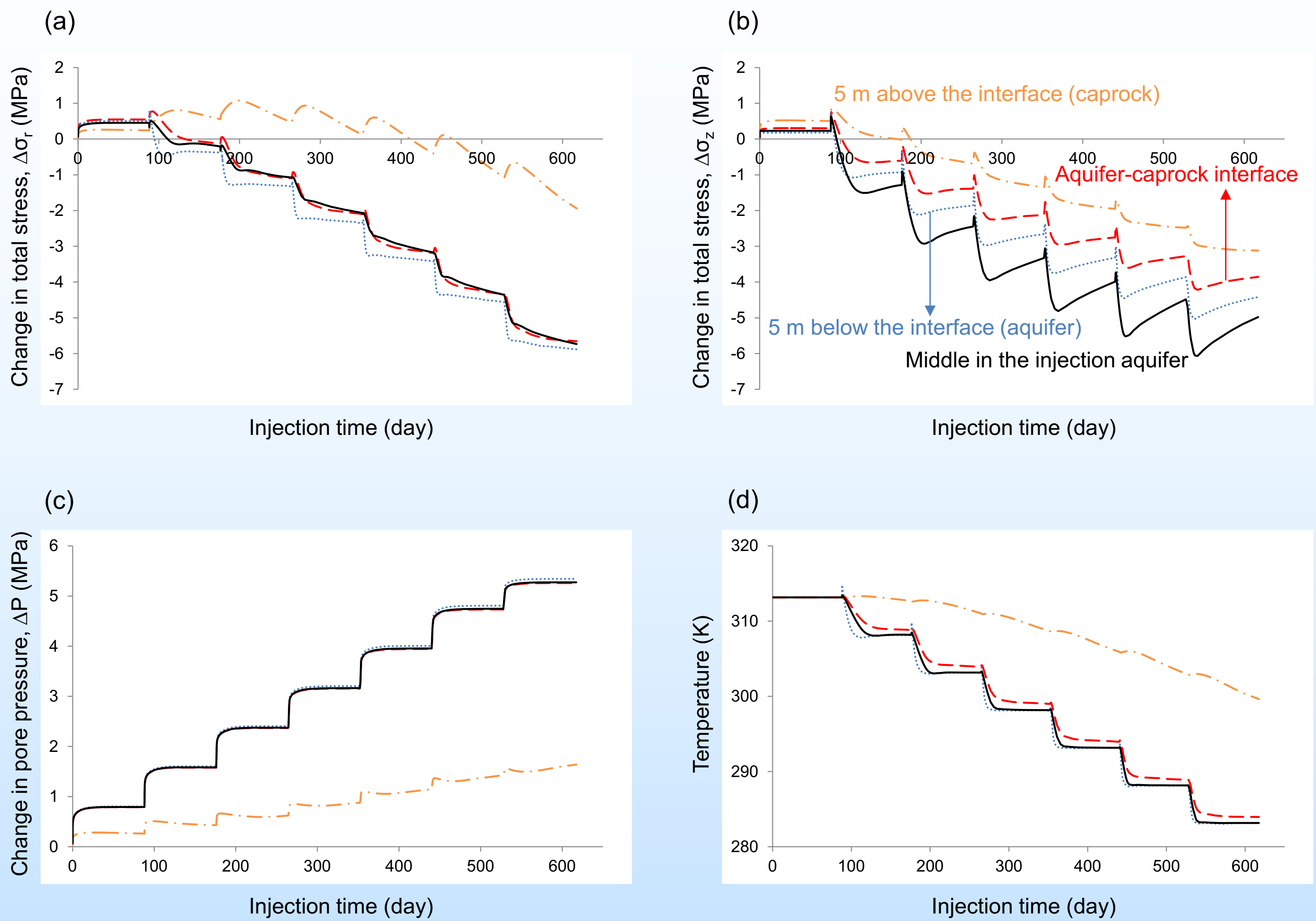
Analytical model



Accomplishments to Date-6



Accomplishments to Date-9



Maximum pressure derivation

$$p_{\max} = \frac{1}{\alpha}\left[\frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\theta - \frac{1}{2}(\sigma_1 - \sigma_3)\frac{\sin 2\theta}{\mu}\right]$$

where, σ_1: major principal stress
σ_3: minor principal stress
θ: angle with respect to minor principal stress

where, $K=\sigma_{h0}/\sigma_{v0}$ (normal-faulting stress regime)
or $=\sigma_{H0}/\sigma_{v0}$ (reverse-faulting stress regime)

Kim, S., and Hosseini, S. A., 2015, Hydro-thermo-mechanical analysis during injection of cold fluid into a geologic formation: International Journal of Rock Mechanics & Mining Sciences, v. 77, p.220-236, http://doi.org/10.1016/j.ijrmms.2015.04.010.