Snøhvit CO_2 Storage Project

FWP-FEW0174 Task 4

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U.S. Department of Energy

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

August 20-22, 2013

Outline

- Benefit to Program
- Project Goals & Objectives
- Technical Status
- Summary & Accomplishments
- Appendix

Benefit to the Program

- The research project is focused on mechanical deformation in response to CO_2 injection at Snøhvit
- An understanding of hydromechanical interactions is essential for effective prediction and monitoring of reservoir performance
- This program meets the Carbon Storage Program goal to support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent

Project Overview: Goals and Objectives

- The project goal is to understand hydromechanical impacts of CO_2 injection into a complex storage reservoir:
  - Study the formation/enhancement of migration pathways within the reservoir
  - Validation of results based on monitoring and characterization data provide by Statoil
  - This work can guide management and monitoring practices for sub sea floor injections and complex geologic structures
- Success is tied to ability to reproduce and predict behavior given available monitoring and characterization data, and provide useful guidance for the field operator

Technical Status

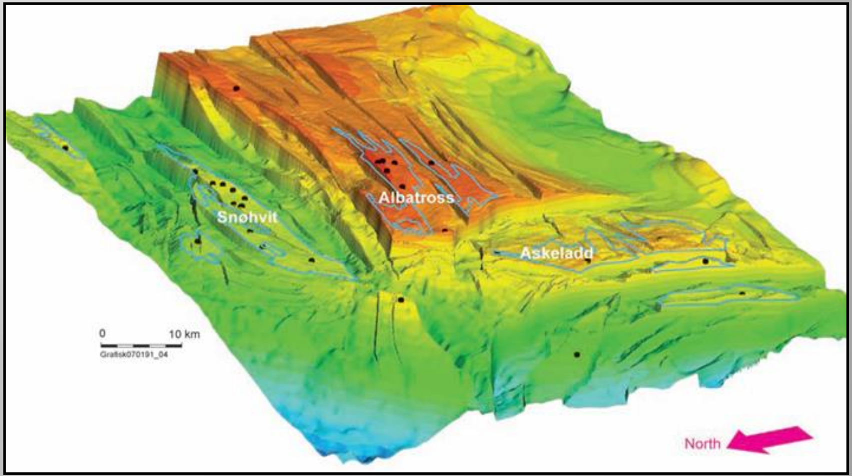
- Schedule was reset by sponsor to October 1st, FY2013, due to contracting & data transfer delays
- First stage of project was completed:
  - Discrete Fault Activation Analysis under Stress Uncertainty
  - Preliminary Hydromechanical Analysis – Reservoir Pressure Response
- New data received on July 2013

Accomplishments to Date

- Pre-study completed
- Site characterization and geo-model completed
- Discrete fault activation & stress uncertainty analysis complete
- Preliminary analysis of pressure response in reservoir completed

Snøhvit CO_2 Project

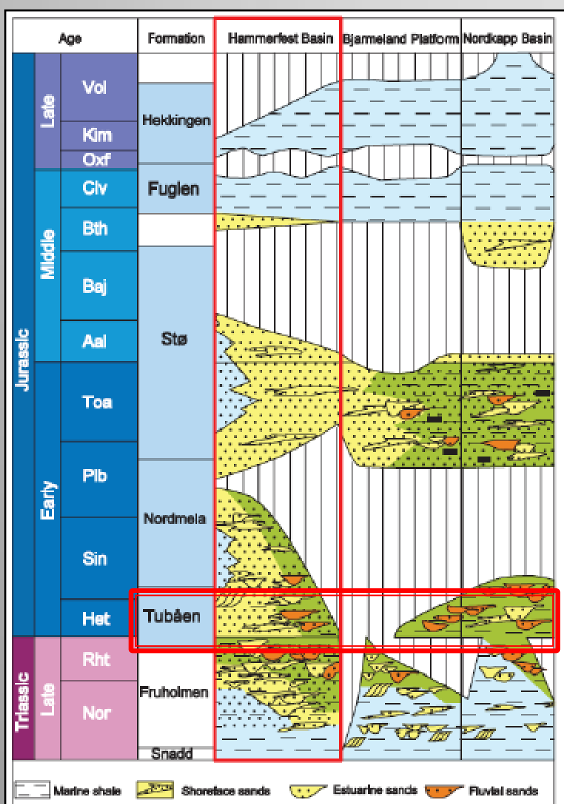
- Gas fields with a 5 – 8 % CO_2 content, which needs to be reduced before liquefaction
- Separated CO_2 was re-injected into Tubåen Fm. at ~2600m depth
- Injection began in 2008, but in 2010 Statoil announced **storage capacity in Tubåen was lower than expected**. Have since moved injection to another formation



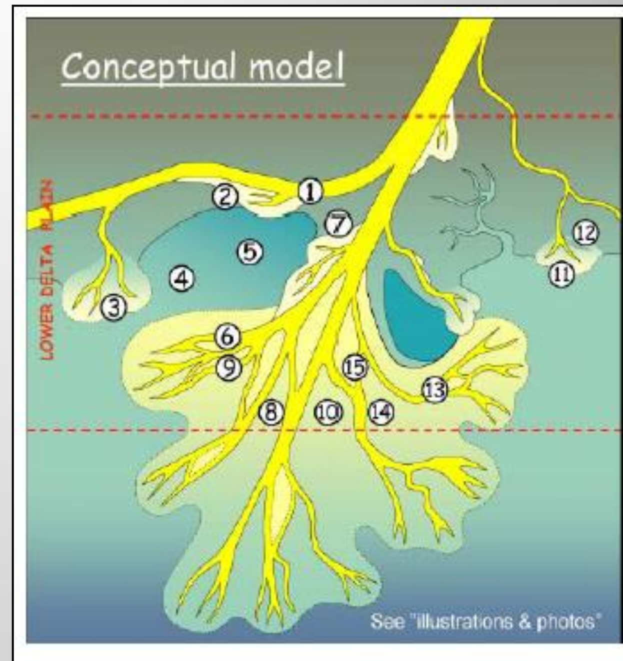
Structural diagram of Hammerfest Basin

Stratigraphy

- Storage target: **Tubåen Fm.** ~2600 m depth.
  - 45-130 m clastic wedge (over ~50 km)
  - Individual channels & subordinate shales
  - Porosity 1-16%, Permeability 130-880 mD
- Caprock: Nordmela Fm.
  - Porosity ~13%, Permeability 1-23 mD



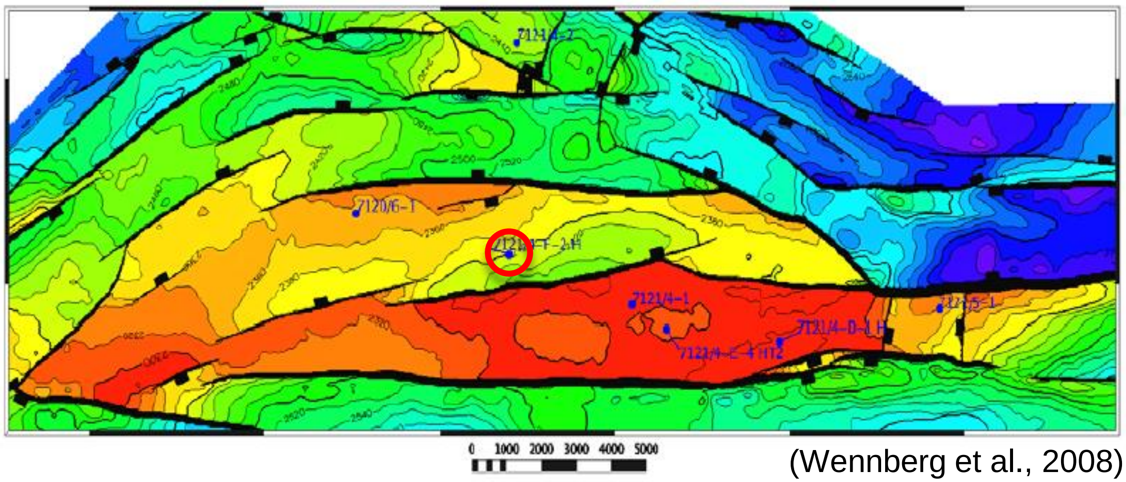
Wennberg et al., 2008



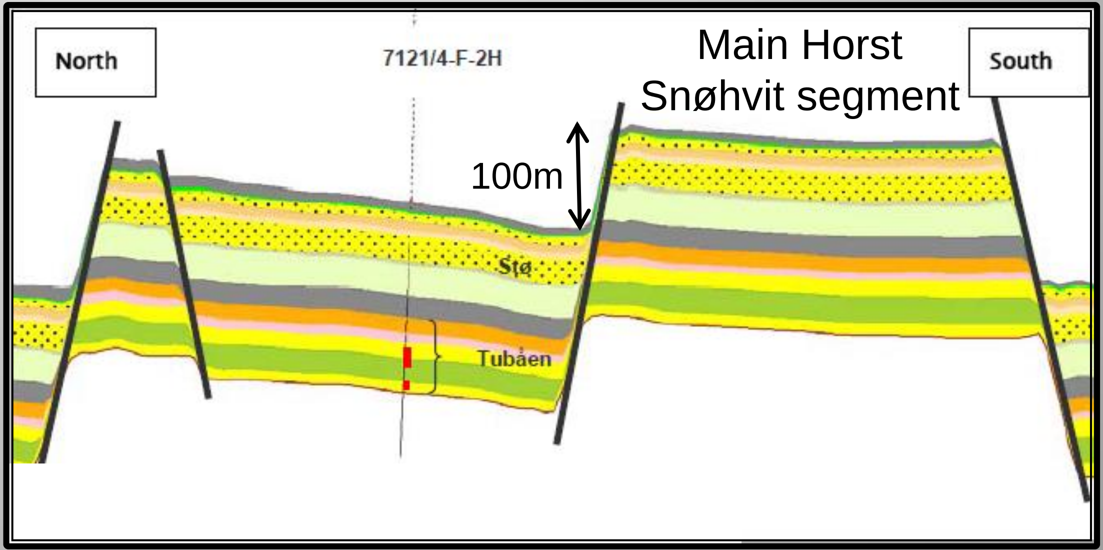
- Delta plain depositional environment, with fluvial distributary channels & some marine-tidal influence
- Highly variable sandstone facies, interbedded with siltstones & mudstones

Structural Configuration

Top of Fuglen Fm. – depth map



(Wennberg et al., 2008)

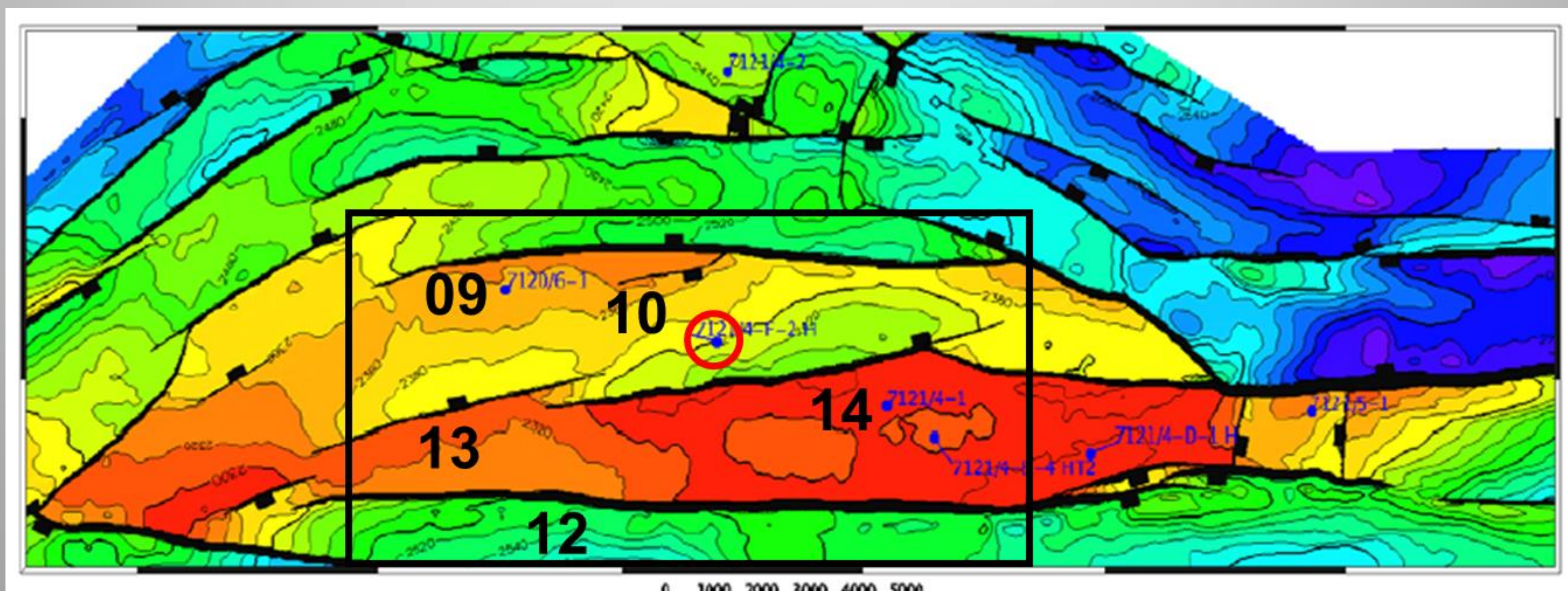


Structural complexity of the site raises many interesting hydromechanical questions

1. What is the role of the bounding faults at the site?
   - Are they reservoir seals or potential leakage pathways? Is there a risk of contaminating the producing gas?
2. Why was storage capacity lower than expected?
   - Is it a completely compartmentalized system? Is it a function of the depositional setting? What is the role of observed faults/fractures?

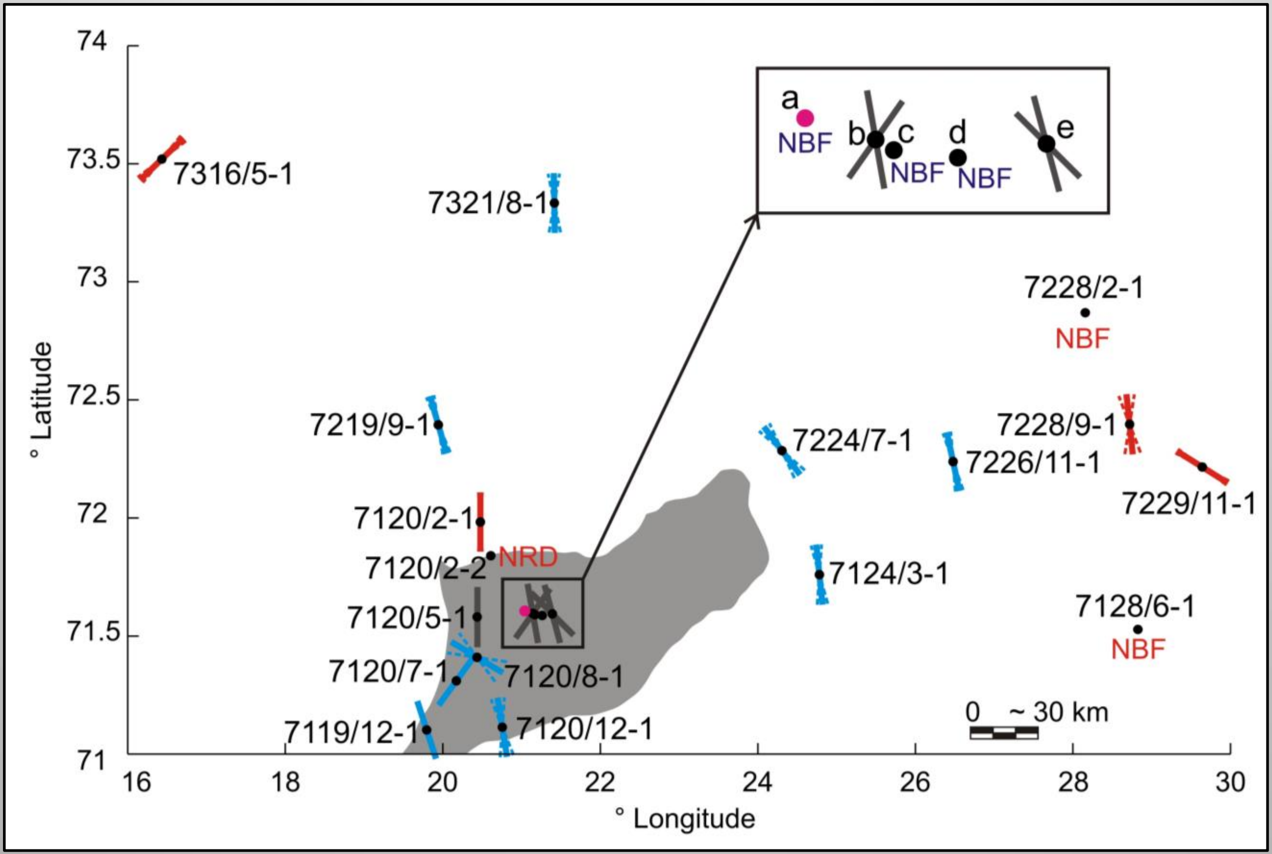
1.- What is the role of the bounding faults

- Fault Stability Analysis: Coulomb Criteria considering thermo poro-elasticity effects
- Uncertainty Analysis using PSUADE (Problem Solving environment for Uncertainty Analysis and Design Exploration



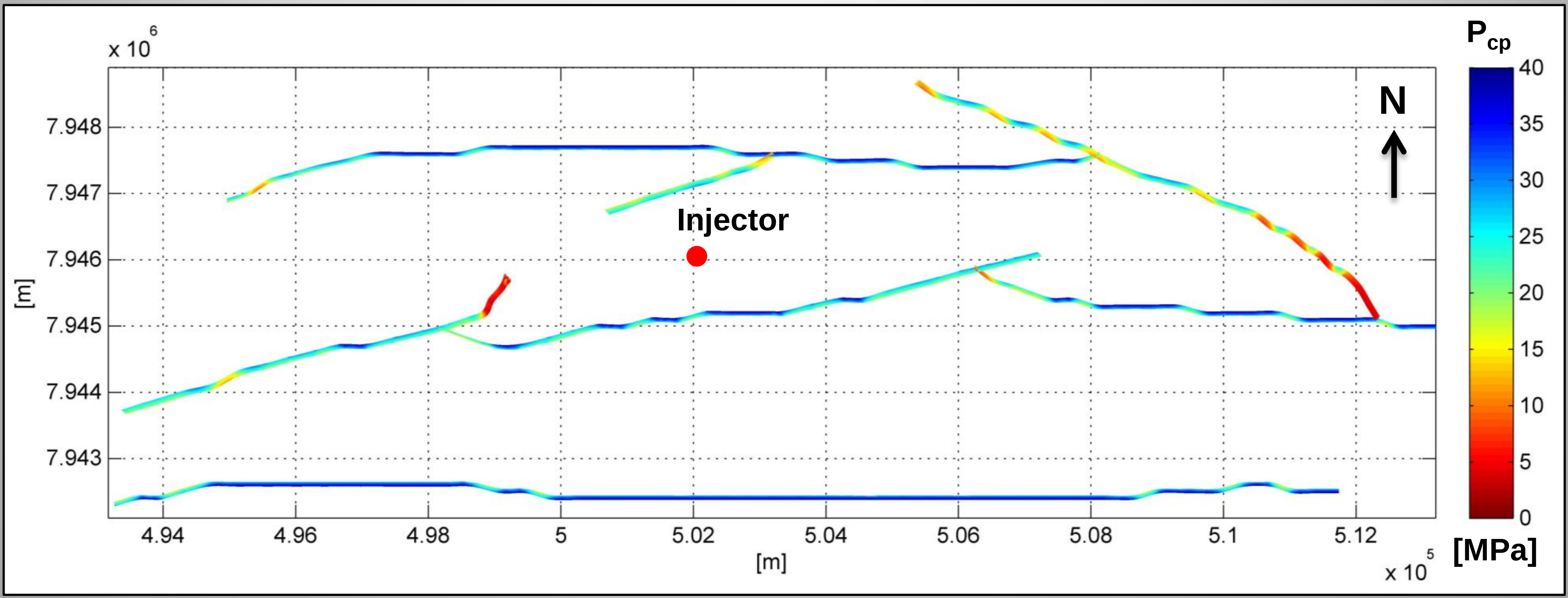
Stress Uncertainty

Up to 90 degrees variations in reported S_{Hmax} Azimuths



Base Case modeled as NS S_{Hmax} Azimuth Strike Slip regime

Fault Stability Analysis indicates fairly stable bounding faults (NS S_{Hmax})



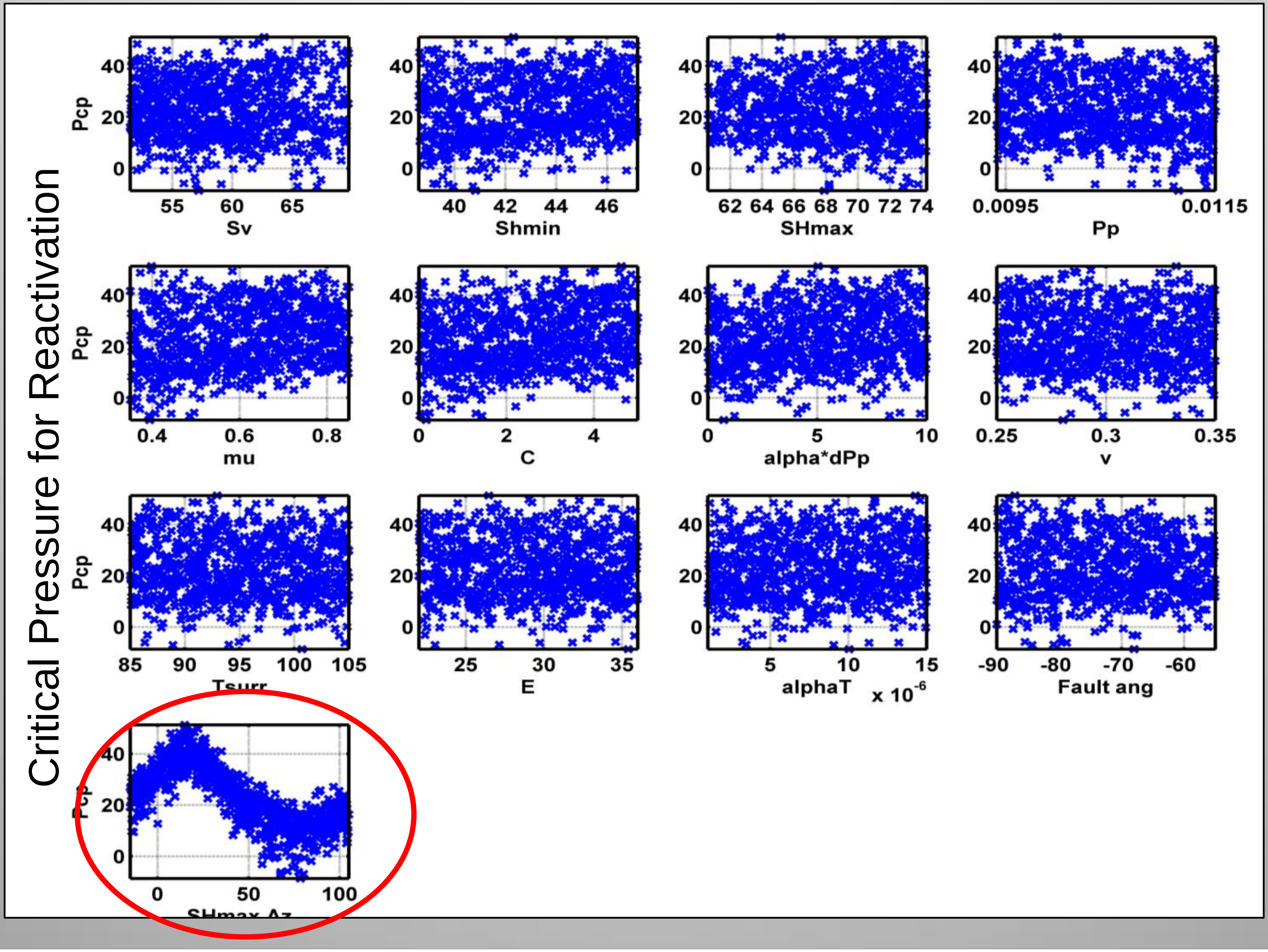
Fault traces color-coded by amount of extra pressure (P_{cp}) necessary to initiate slip (Base Case scenario: SS environment with NS S_{Hmax} direction)

Uncertainty Analysis - PSUADE

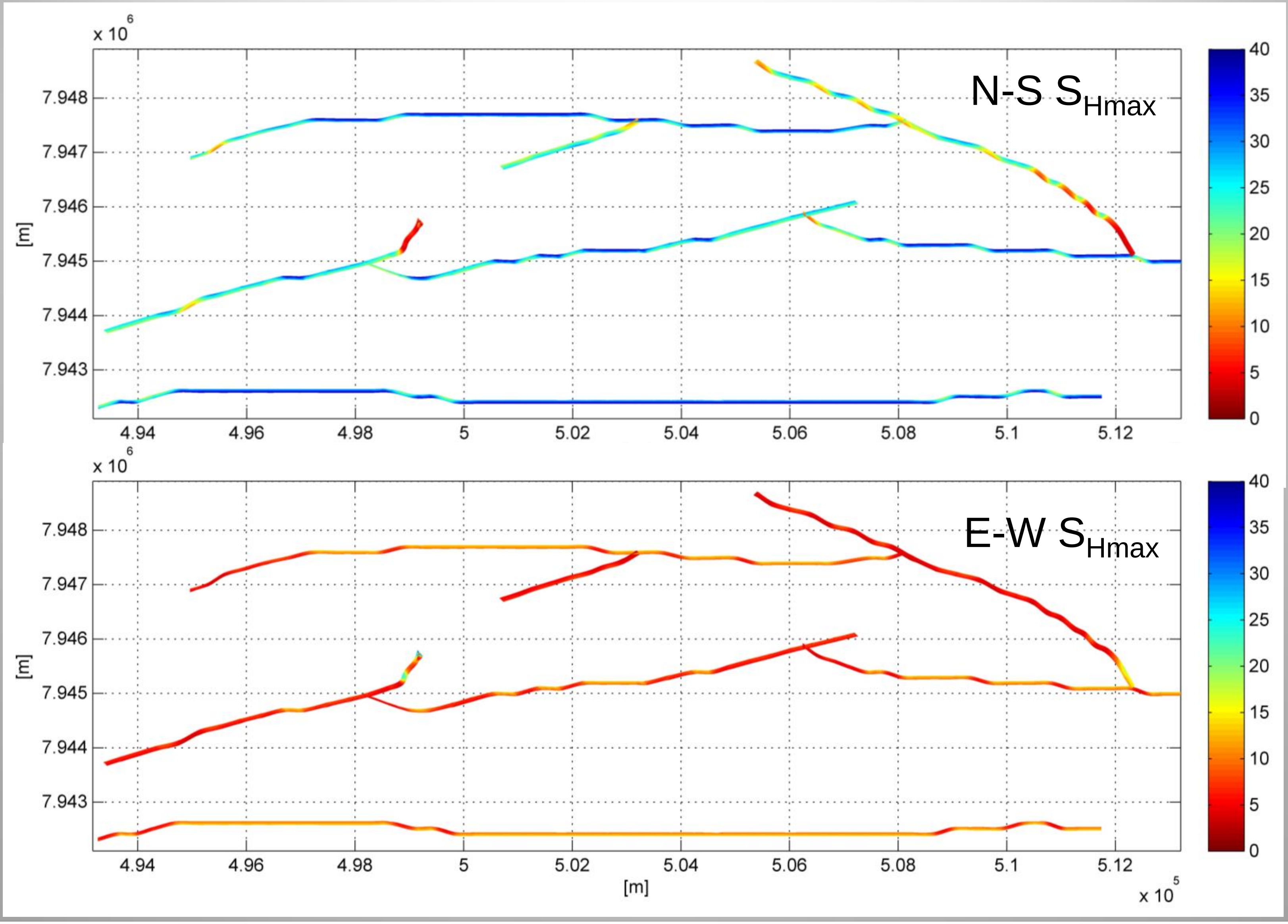
- 13 Parameters
- 1000 samples produced with Latin hypercube sampling method

Variable	BC	Min	Max	Units
S_v	60.6	51.5	69.7	MPa
S_{hmin}	43	38.6	47.2	MPa
S_{Hmax}	65	60.6	74.3	MPa
P_p	28	25.2	30.8	MPa
μ	0.6	0.35	0.85	
C	0	0	5	
$\alpha*dP_p$	0	0	10	MPa
ν	0.25	0.25	0.35	
T	95	85	105	°C
E	35	22	36	GPa
αT	$1.5e^{-5}$	$1e^{-6}$	$1.5e^{-5}$	1/°C
Fault ang	-85	-55	-90	°
S_{Hmax} Az	0	345	105	°

UQ Analysis indicates S_{Hmax} Az as main uncertainty



Faults ~ 25-35% less stable with EW S_{Hmax}



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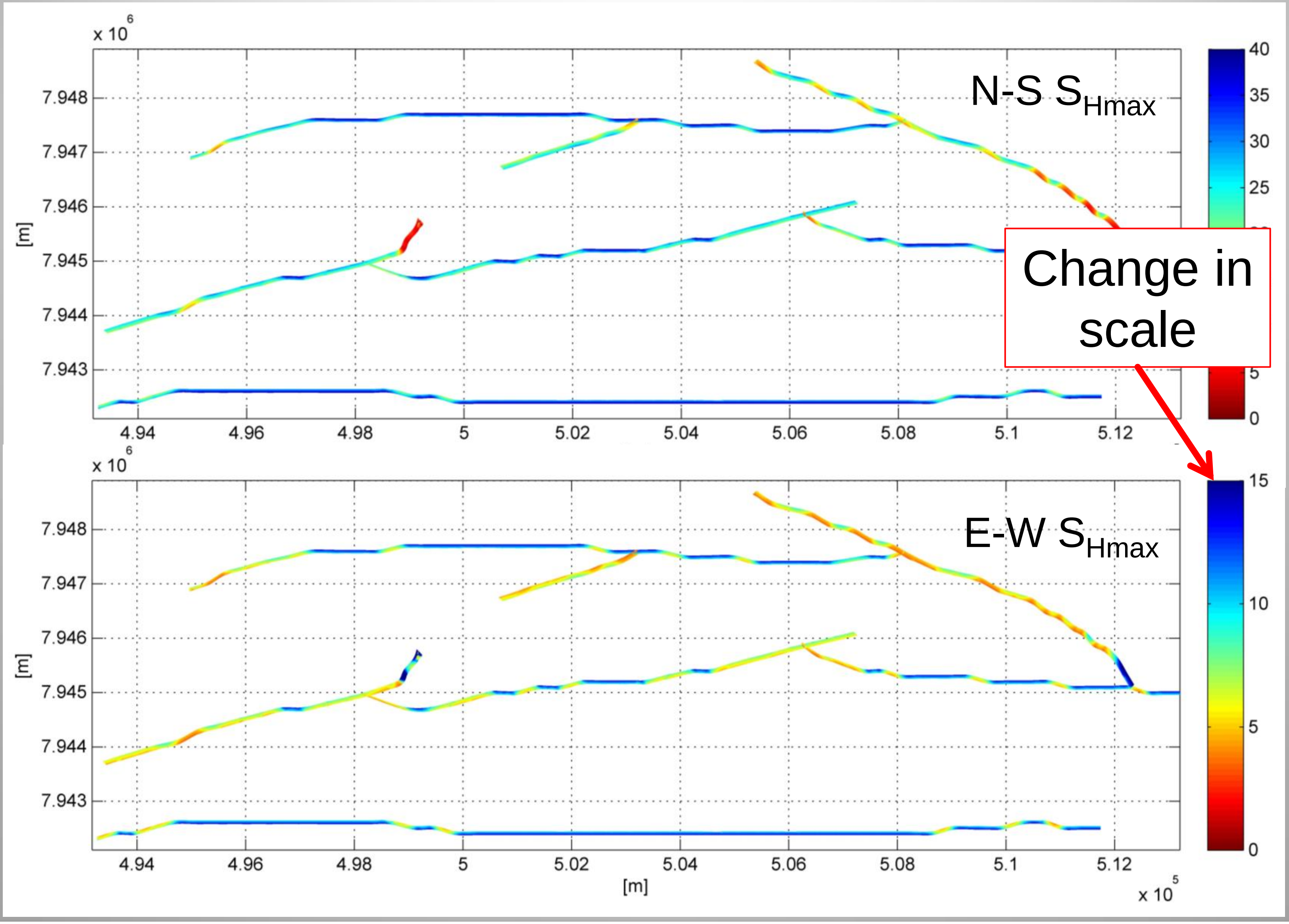
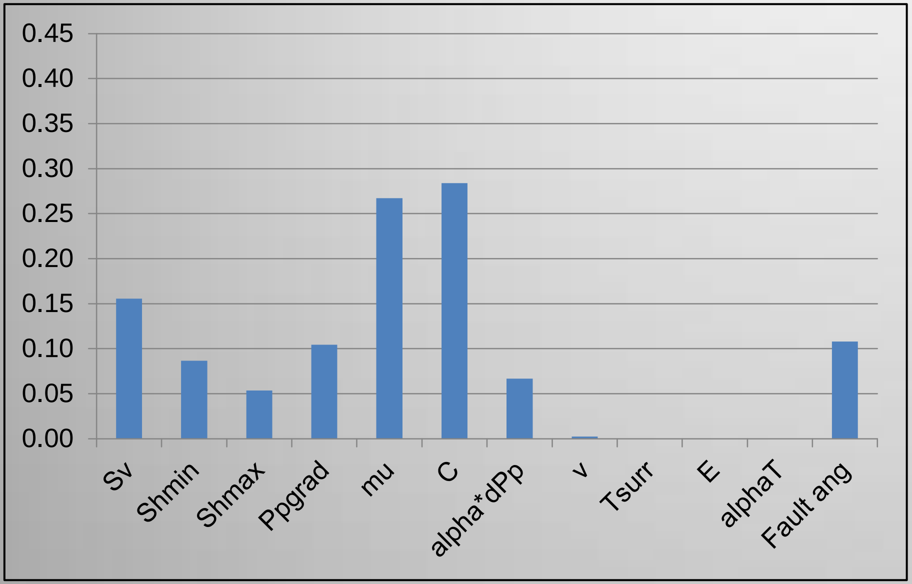
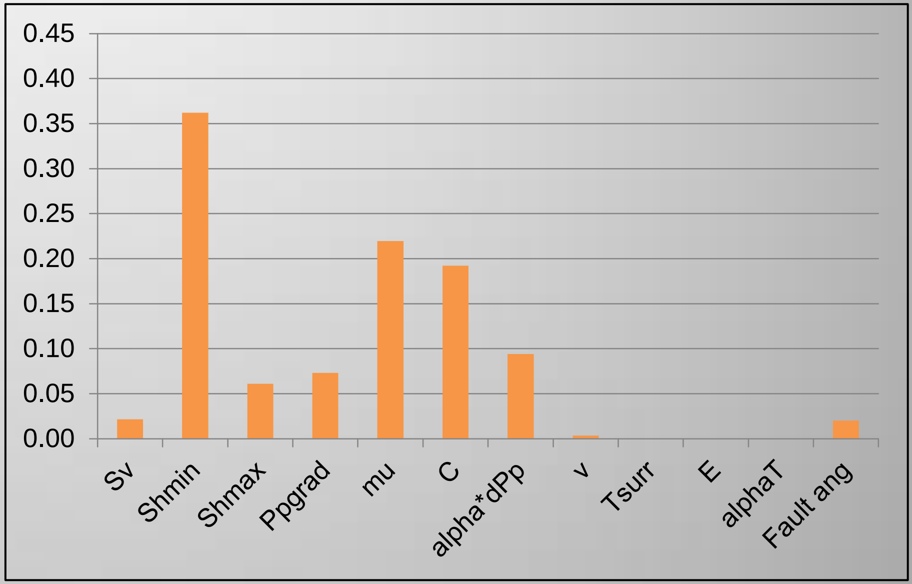


Refined Uncertainty Analysis – 12 variables (no S_{Hmax} Az)

NS S_{Hmax}



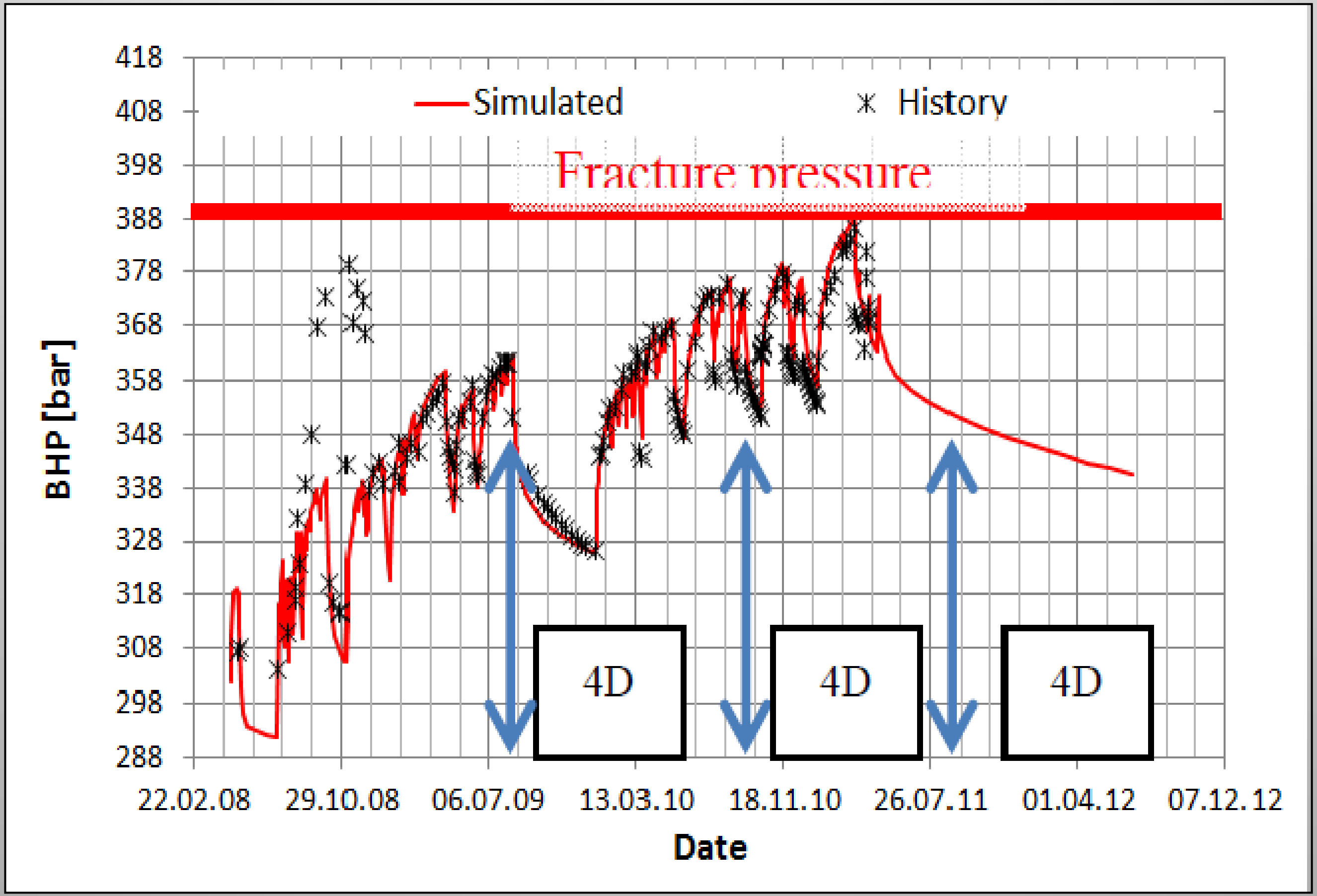
EW S_{Hmax}



Example: sensitivity indexes for Fault 10

Stress tensor components, fault ang, µ, C, Pp and ΔP indicated as the most influential parameters

2.- Why was storage capacity lower than expected



Previous Analysis (Hansen et al. 2012)

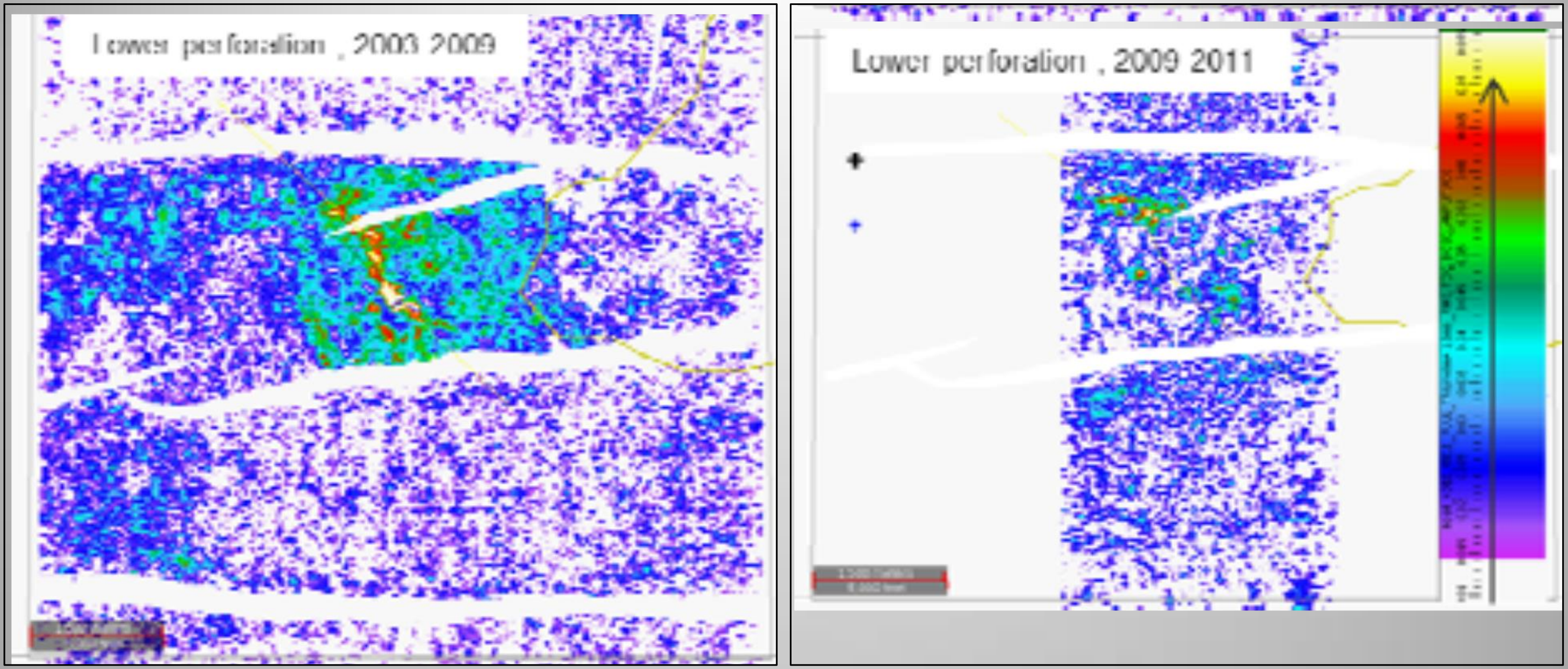
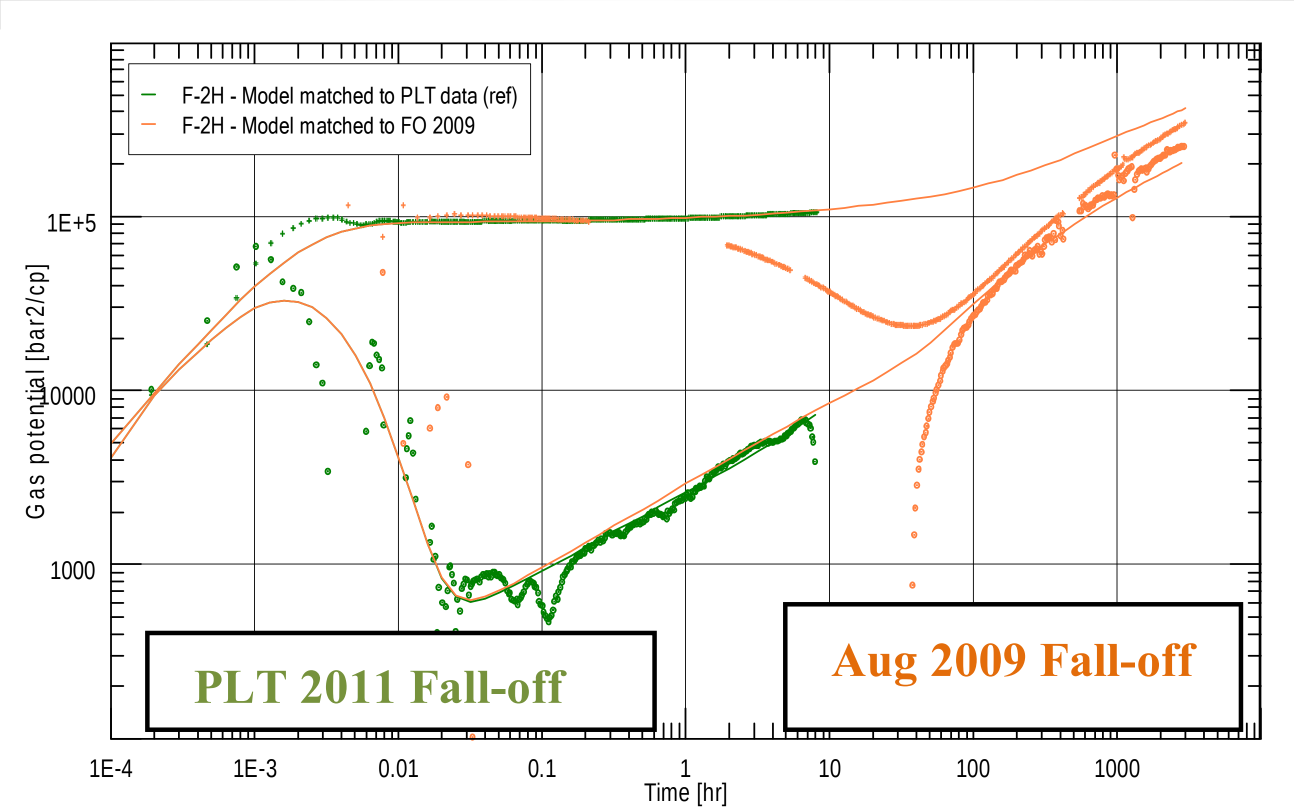


Figure: 4D difference amplitude maps, lower perforation, from (Hansen et al, 2012). Left: 2003-2009, Right: 2009-2011.

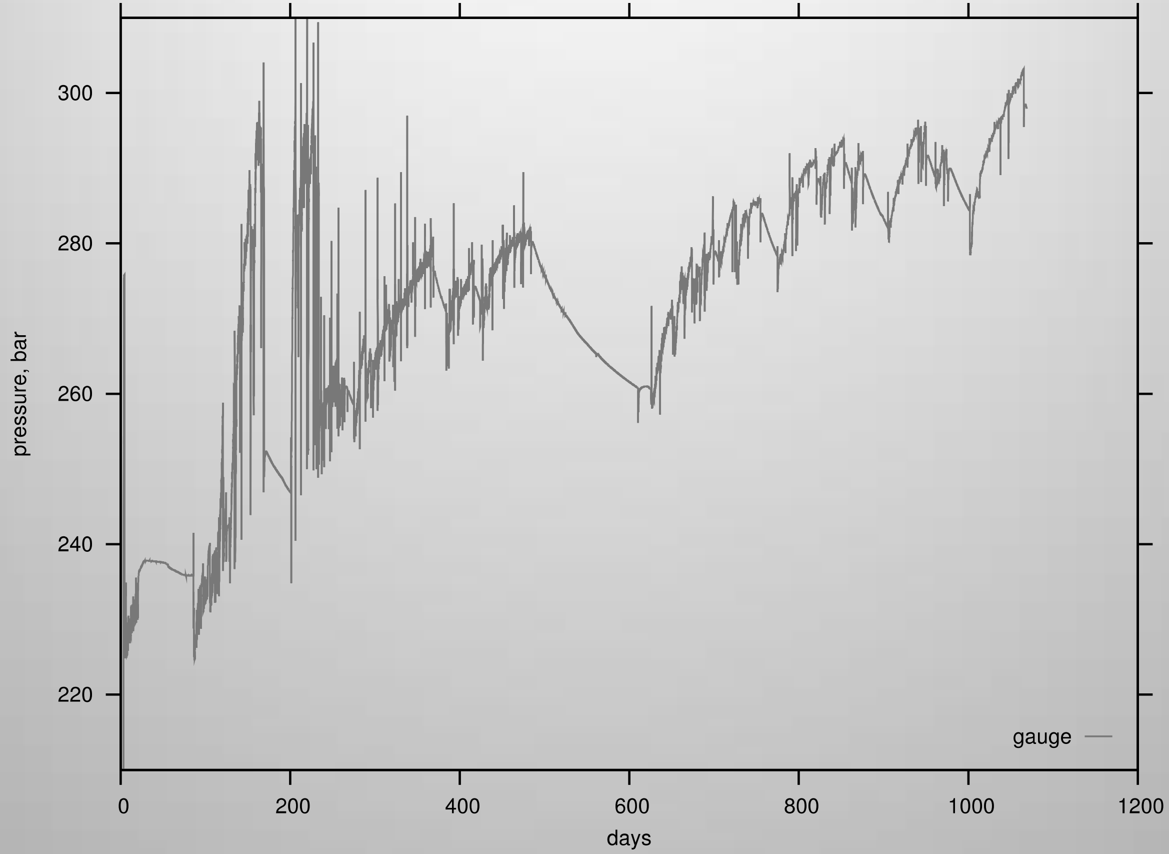
- 4D seismic reveals distinct channels & vertical stratification
- Lower perforation taking ~80% of the injection

Previous Analysis (Hansen et al. 2012)



- Previous falloff analyses suggested flow barriers at 110m, 110m, and 3000m from injector
- PVT challenges encountered using gauge ~850m above reservoir (2009 data)

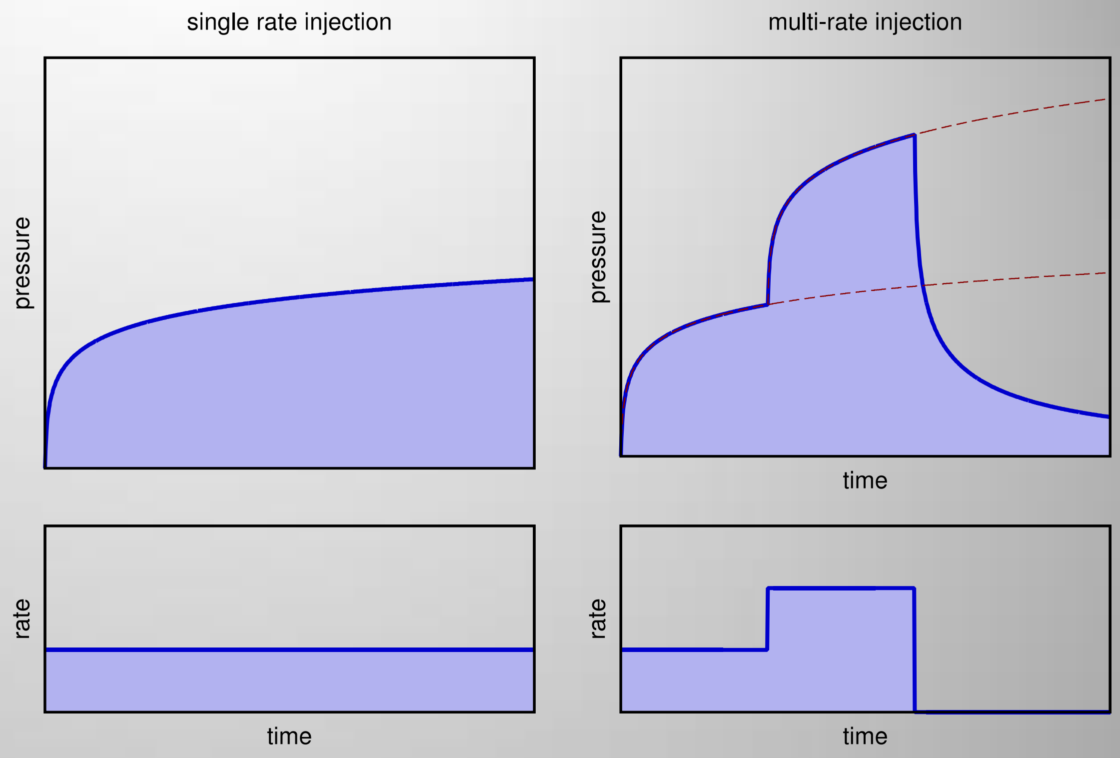
Is this a closed reservoir? Does rate, pressure & temperature history imply changes in injection behavior?



Examine entire rate, pressure, and temperature history from the gauge at 1782 mTVDss

Approach: Superposition Analysis

- Multi-rate injections are difficult to analyze.
- Can often use the principle of superposition to simplify the analysis (single-phase approximation).
- Given pressure and rate history, we solve for a “characteristic” pressure curve (as a linear least squares problem).

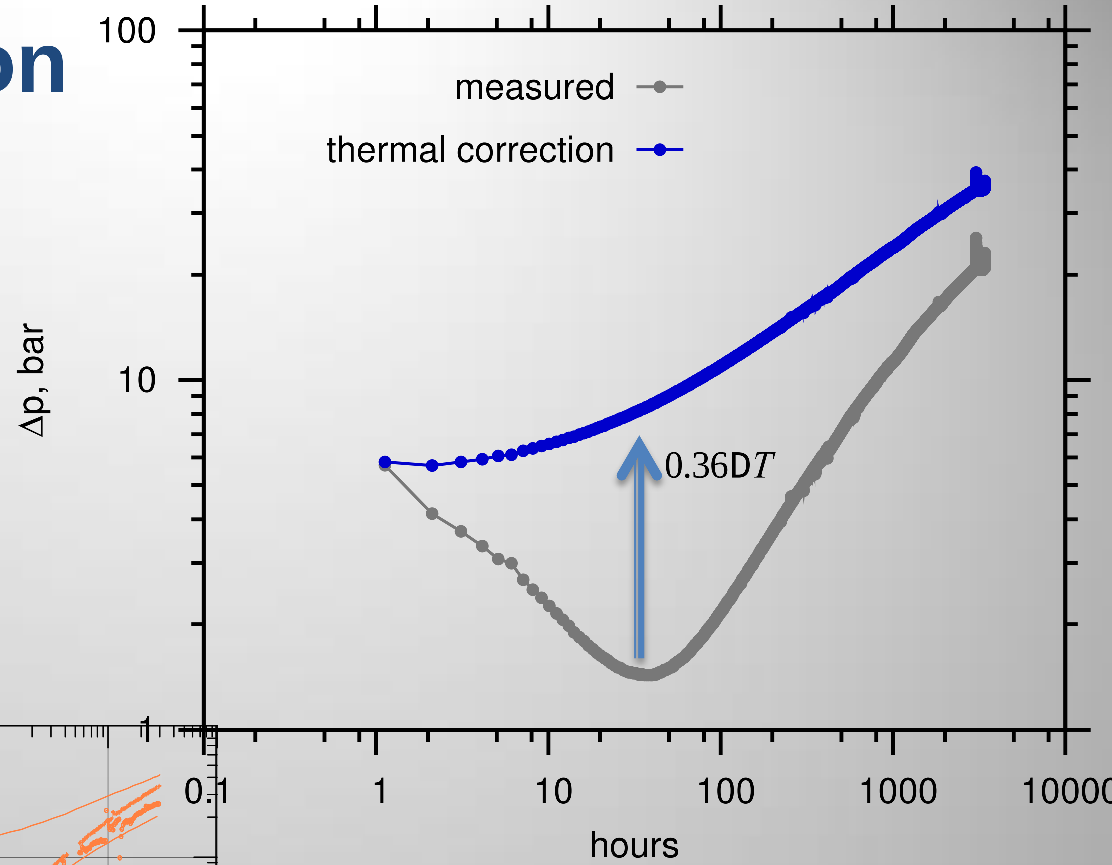


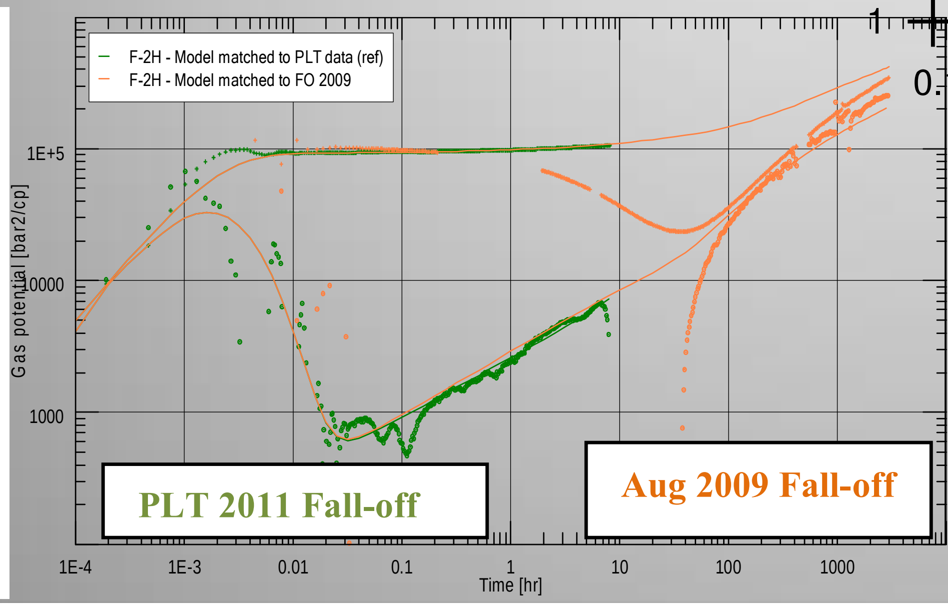
Single rate: $p(t) = q \cdot p_C(t)$

Multi-rate: $p(t) = \sum_i (q_{i+1} - q_i) \cdot p_C(t - t_i)$

Thermal Correction

- Adding simple thermal correction ….

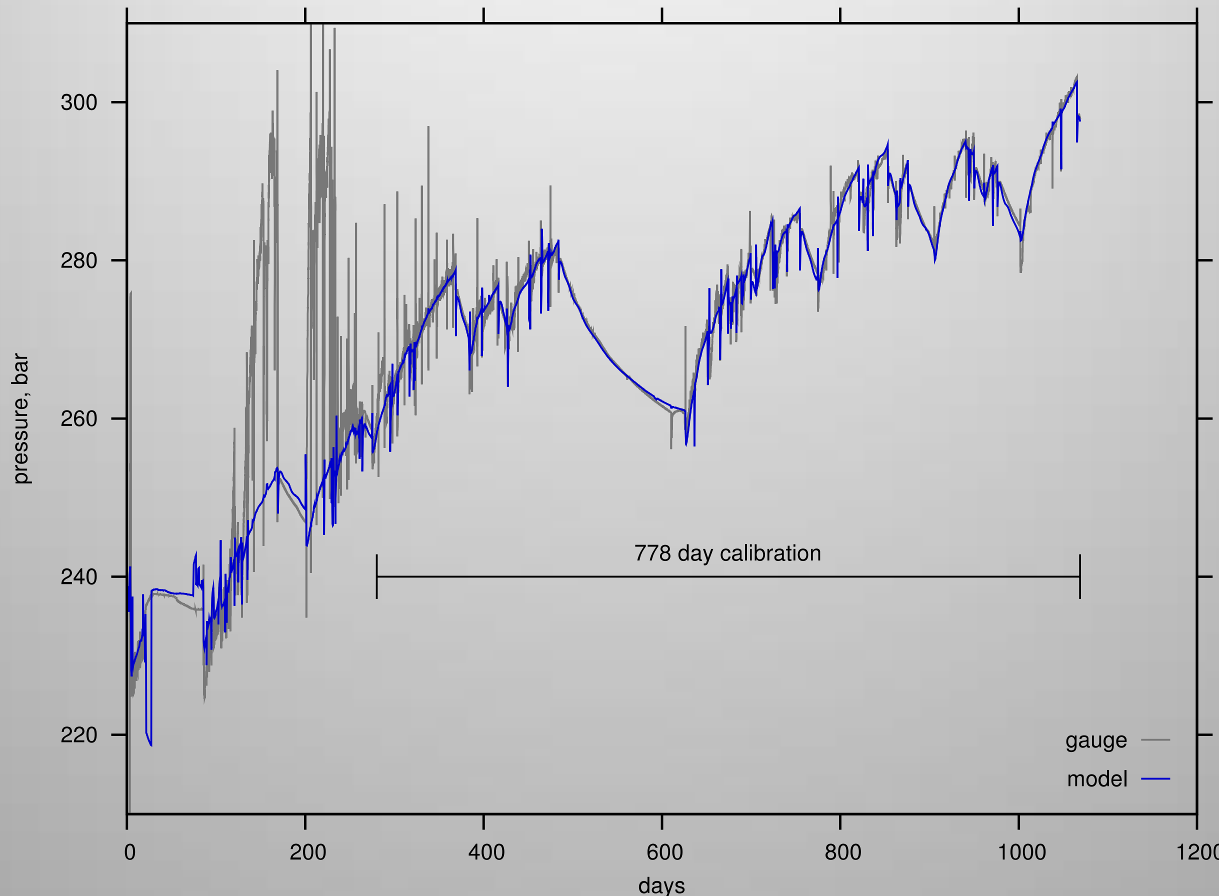




… the gauge data becomes consistent with PLT observations.

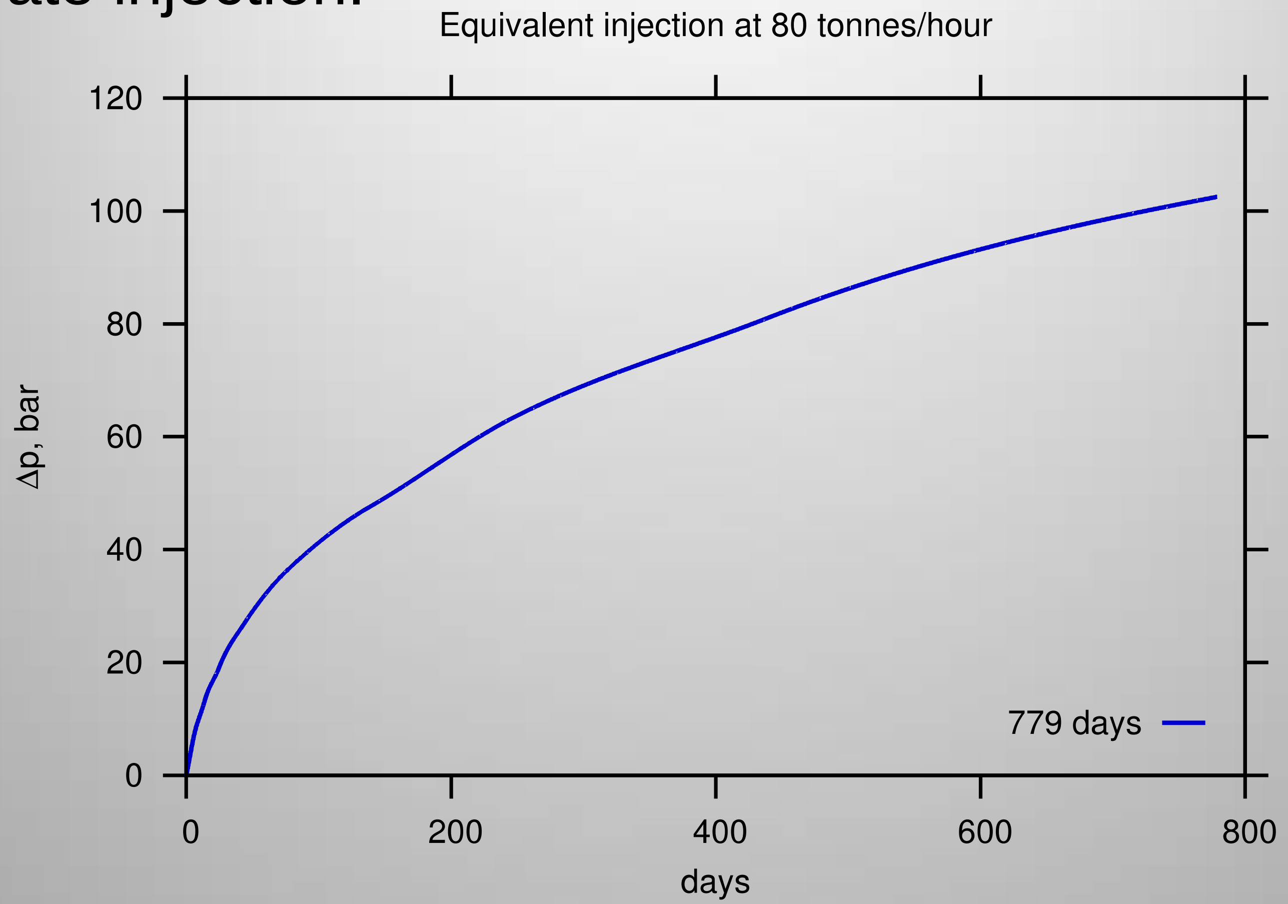
Best-fit Results

- All data used for calibration, except early salt-precipitation period
- Fit with one $p_C(t)$ curve



Best-fit Results

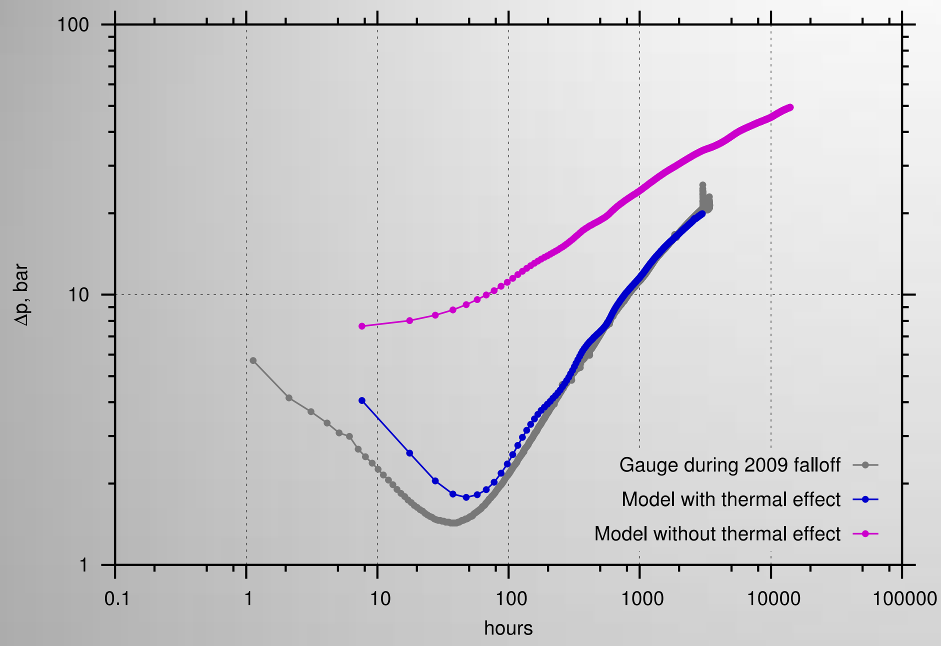
- Resulting $p_C(t)$ represents an equivalent constant-rate injection.



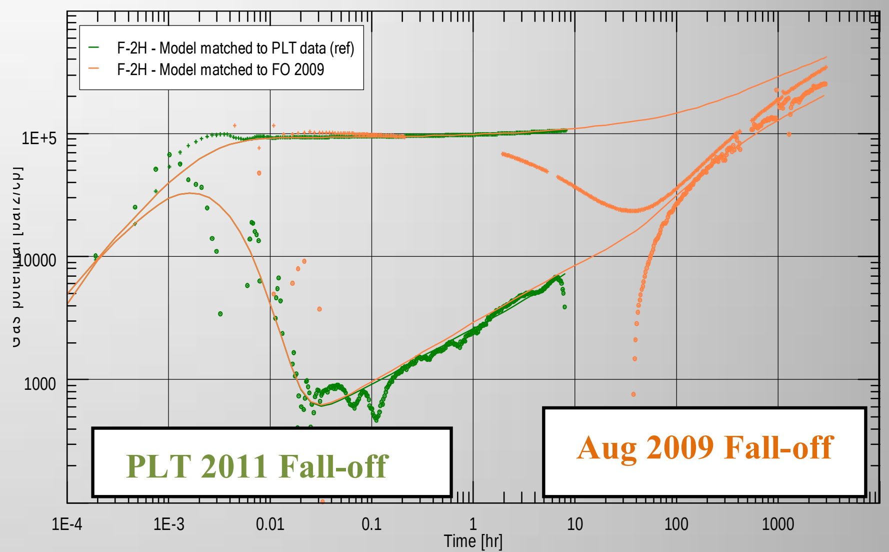
Available data constrains the shape of this curve out to 779 days (the calibration period).

Barrier indications in the 2009 falloff

Log-log plot of the 2009 falloff (real pressure)



Falloff analyses from (Hansen et al, 2012)



- Superposition provides additional data beyond 2009 falloff period (779 vs. 142 days).
- Multiple barriers appear early in the falloff history, but no strong evidence of additional barriers appearing after ~100 hours.

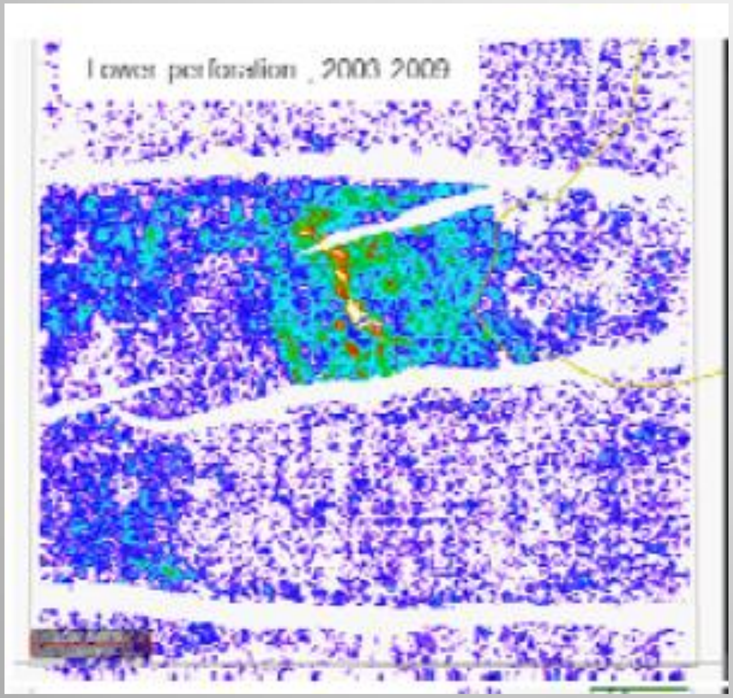
Observations from Pressure Analysis

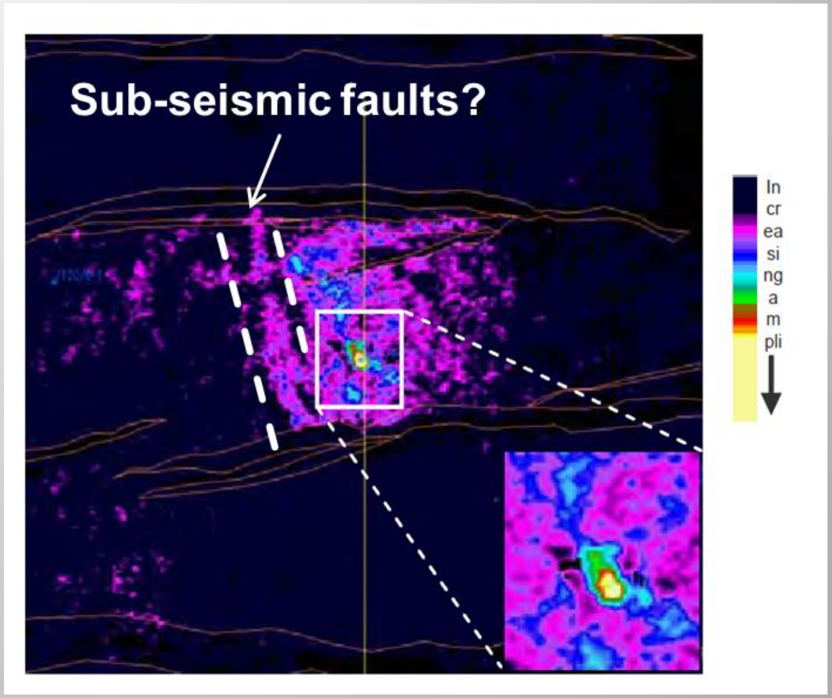
- Reservoir does not exhibit significant changes in injection behavior over time. No evidence of large geomechanical or permeability changes.

- Reservoir does not appear completely closed, and had not reached pseudo-steady state.

4D seismic analysis suggests stratigraphic compartmentalization, can it also have a structural component?

4D difference amplitude maps

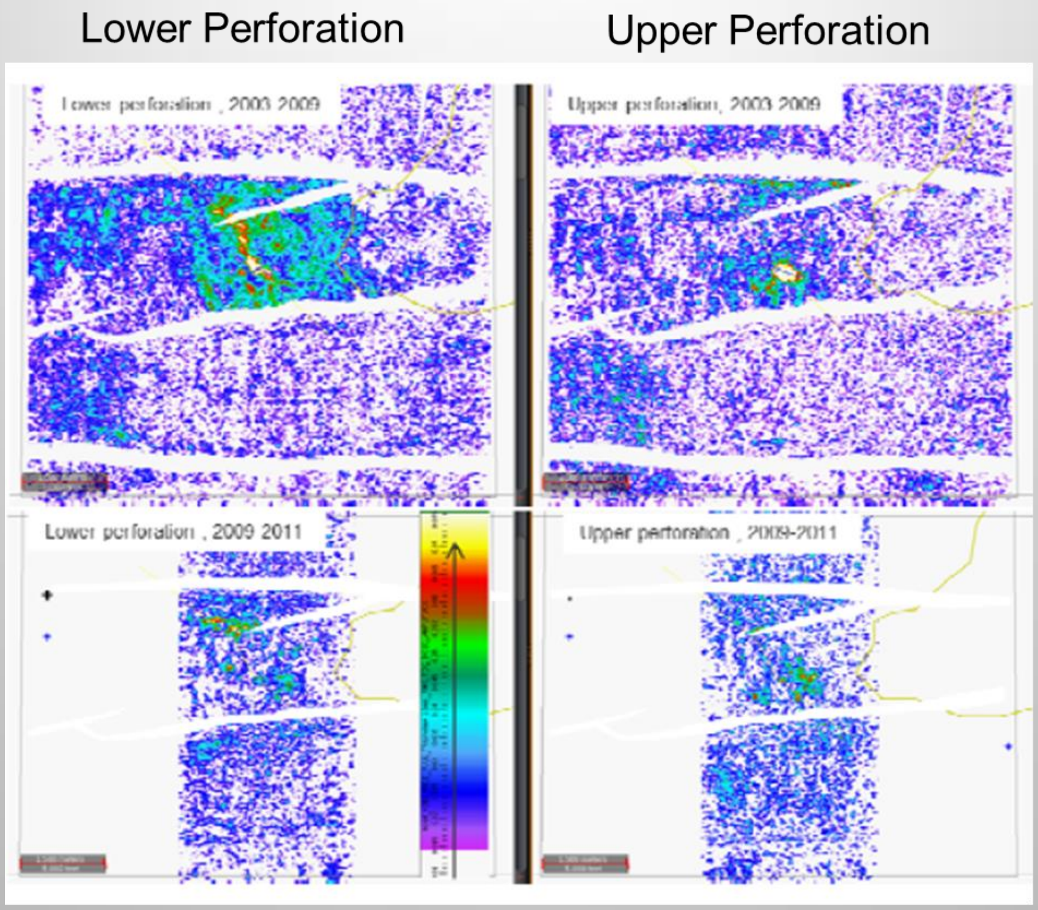




Hansen *et al*, 2012

Hypothetical sub-seismic faults (Az = 335-355º) expected "permeable" under NS S_{Hmax}

Reservoir does not appear completely closed, is it possible a local vertical migration at F10?



Hansen *et al*, 2012

F10 expected "sealing" under NS $S_{Hmax,}$ but "permeable" with EW S_{Hmax}

Summary

- Strong stress uncertainties difficult predictions
- Faults fairly stable under “most likely” stress state: SS & NS S_{Hmax}. Caprock failure would happen before fault reactivation. Under those conditions, it is unlikely that a theoretical sub-seismic fault could act as flow barrier
- Faults are ~ 30% less stable with EW $S_{Hmax,}$ where several segments are close to critically stressed. Fault reactivation could happen before caprock failure if injection continues with risk of gas contamination.

Summary, cont.

- Superposition analysis provides a complement to standard falloff testing, allowing one to analyze multi-rate pressure data over long periods
- Reservoir does not exhibit significant changes in injection behavior over time. No evidence of large geomechanical or permeability changes over time
- Reservoir does not appear completely closed, and had not reached pseudo-steady state. New storage volume was still being accessed at end of injection
- Potential structural component in compartmentalization/fluid migration difficult to assess due to stress orientation uncertainty

Acknowledgments

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- Phil Ringrose, Olav Hansen, Bamshad Nazarian for useful discussions and contributions
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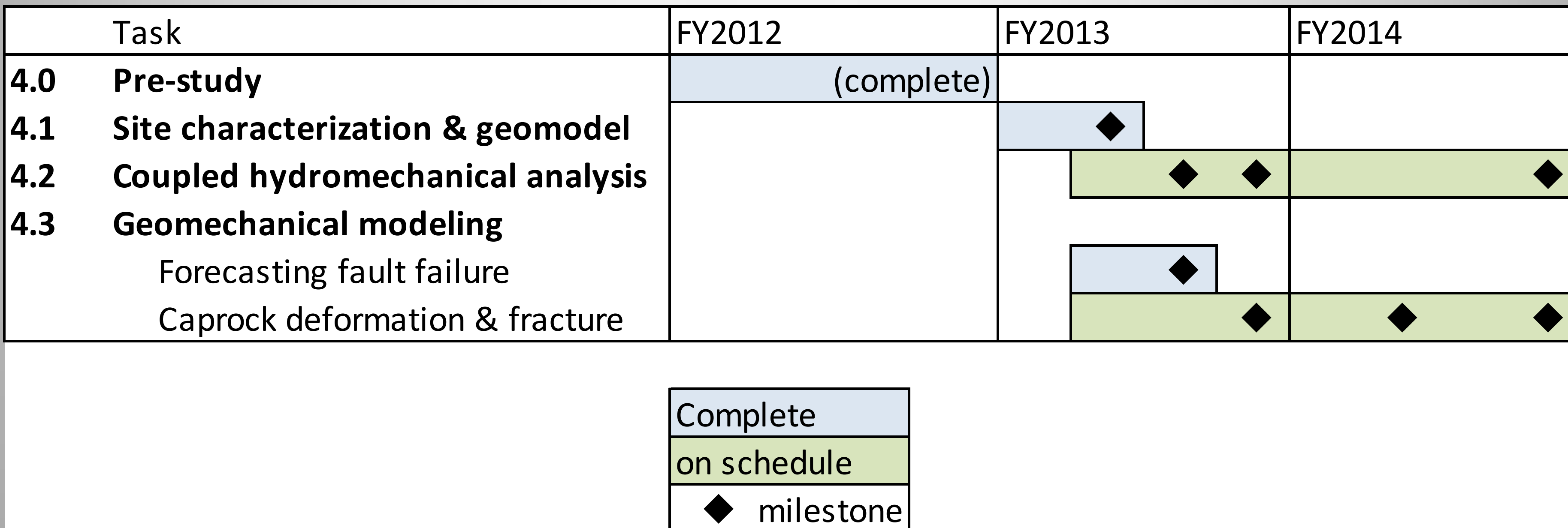
Appendix

Organization Chart

- Carbon Fuel Cycles (Roger Aines)
- Carbon Management (Susan Carroll)
- LLNL Carbon Sequestration Program
  - **Task 1. Active Reservoir Management**
  - **Task 2. In Salah**
  - **Task 3. China**
  - **Task 4. Snøhvit**
  - **Task 5. Carbonates**
- Technical Staff
  - Wolery, Buscheck, Aines
  - McNab, Chiaramonte, Ezzedine, Hao, Foxall, Ramirez, White
  - Friedmann
  - Chiaramonte, White, Hao, Trainor-Guitton
  - Carroll, Hao, Smith
- Expertise
  - Subsurface Hydrology
  - Computational Geomechanics
  - Experimental and Theoretical Geochemistry
  - Seismology
  - Structural Geology

Gantt Chart


Task
FY2012
FY2013
FY2014
4.0 Pre-study
(complete)
4.1 Site characterization & geomodel
4.2 Coupled hydromechanical analysis
4.3 Geomechanical modeling
Forecasting fault failure
Caprock deformation & fracture
Complete
on schedule
milestone

Bibliography

Journal Papers in Preparation:

- Chiaramonte, L., White, J.A. and Trainor-Guitton, W, Effect of Stress Field Uncertainty on Modeling Geomechanics and Seal Integrity for CO_2 Storage Sites, (in preparation)
- White, J.A. and Chiaramonte, L., Pressure Analysis, (in preparaation)

Peer Reviewed Papers:

- Chiaramonte, L., White J.A., Hao, Y., and Ringrose, P., 2013, Probabilistic Risk Assessment of Mechanical Deformation due to CO_2 Injection in a Compartmentalized Reservoir, Proceedings of the 47th U.S. Rock Mechanics / Geomechanics Symposium, San Francisco, CA, 23-26 June
- Chiaramonte, L., White J.A., and Johnson, S., 2011, Preliminary geomechanical analysis of CO_2 injection at Snøhvit, Norway. Proceedings of the 45th U.S. Rock Mechanics / Geomechanics Symposium, San Francisco, CA, 26-29 June

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