Assessing Geomechanical Risks at GCS Sites Using the State of Stress Assessment Tool

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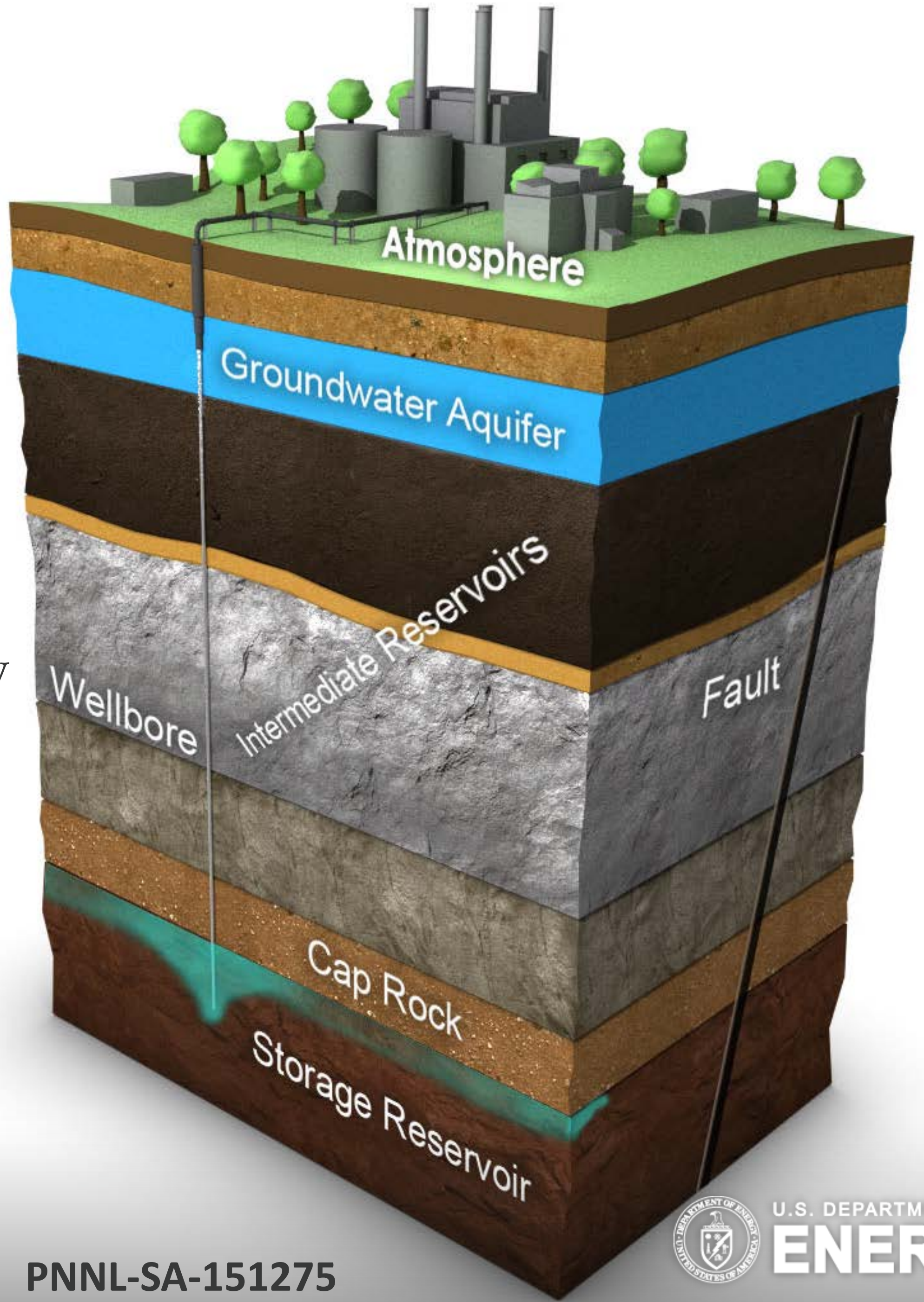
Underground Injection Control Conference and NRAP Workshop, San Antonio, Texas

February 19, 2020

NRAP
National Risk Assessment Partnership



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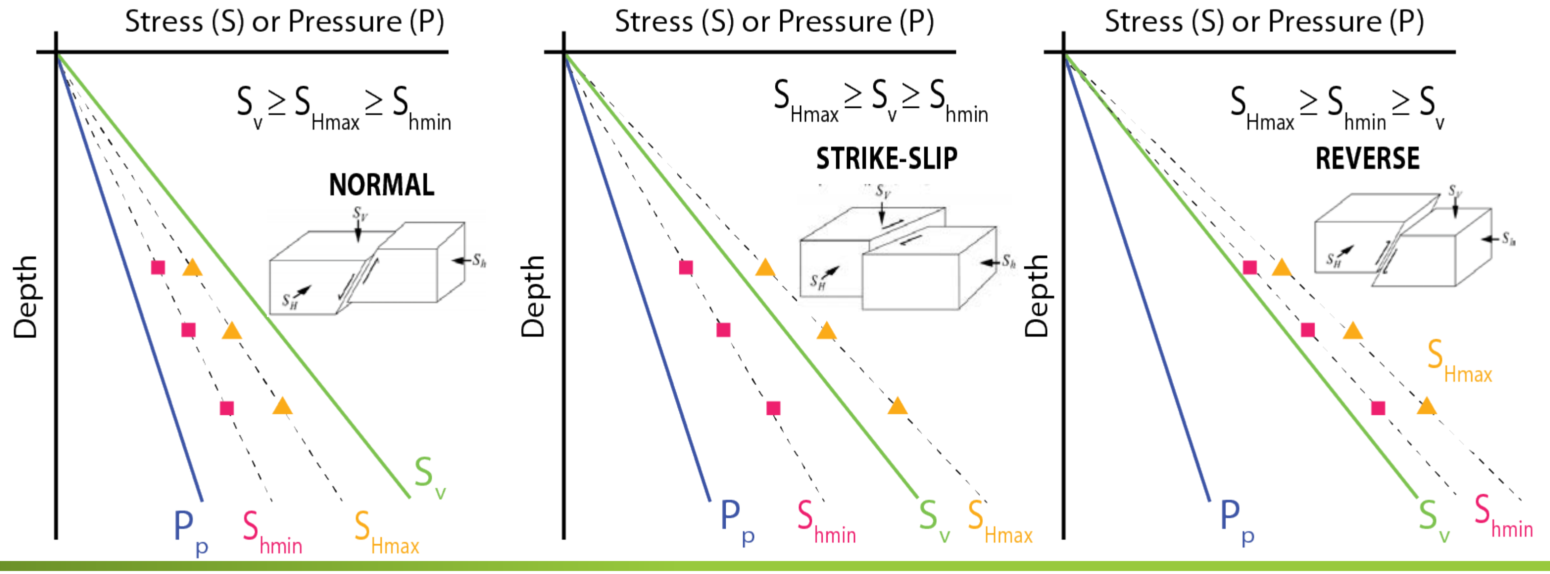
Outline

- Establishing a common ground: Principles and Definitions
- Geomechanical risks at GCS sites
- Geomechanical characterization
- UIC Class VI requirements
- Using SOSAT to assess geomechanical risks
- Example Application: FutureGen 2.0 Site

State of Stress

- **What is the "State of Stress"?**
  - Compressive stress exists everywhere at depth in the earth
  - The state of stress is the estimation of both the magnitude and the orientation of those stresses
  - Need to be determined to perform safe subsurface operations



Variation of relative stress magnitude with depth for the three Andersonian stress regimes (tectonic regime)

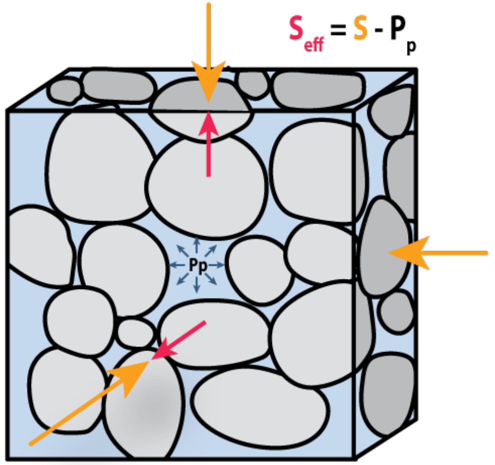
Establishing a common ground: Principles and Definitions (2)

Changes in stresses associated to CO_2 injection

- **Pore pressure and stress:**
  - Rock strength is controlled by effective stress (S_{eff} = S- Pp) (Terzaghi)
  - Fluid injection decreases the effective stress in the reservoir

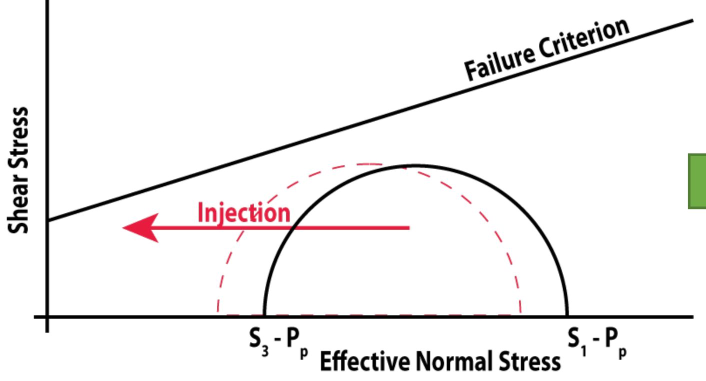
- **Poroelasticity: pore pressure/stress coupling**
  - Stresses are a function of **elastic properties**
  - Stresses evolve with pore pressure (**"stress path"**):

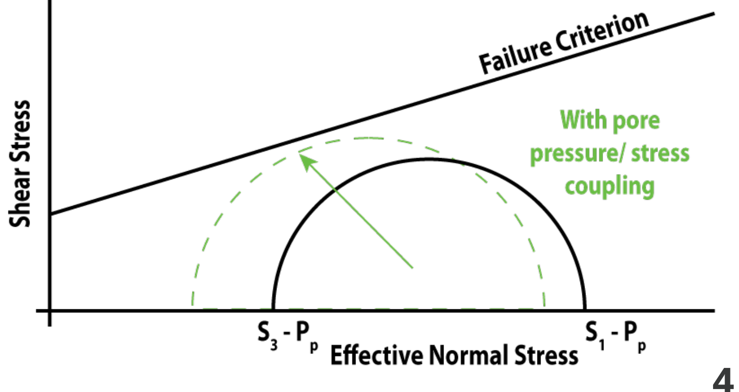
$$\Gamma = \frac{\Delta S_h}{\Delta P_p}$$



Terzaghi Effect

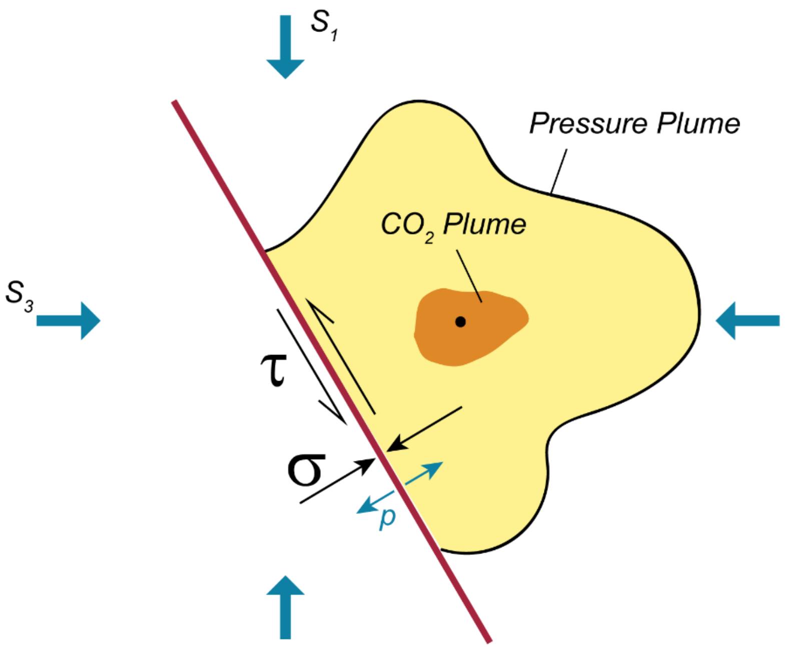
Reactivation of pre-existing fault





Geomechanical risks associated with CO_2 injection

- CO_2 injection operations and associated pressure build-up in the reservoir alters the state of stress
- These changes from the initial reservoir conditions may:
  - affect existing **fault stability**
  - lead to **creation of new fractures (hydraulic fractures)**
- Geomechanics-related risks include:
  - Induced seismicity (property damage, public acceptance)
  - Contamination of drinking water with brine or CO_2
- **Critical to build a geomechanical model to avoid these risks!**



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Geomechanical characterization

- Optimal characterization data needed to build a geomechanical model

Parameter	Acquisition method
Vertical Stress (S_v)	Density logs
Minimum horizontal stress (S_{hmin})	Geomechanical tests (e.g.,minifrac, extended leak-off)
Maximum horizontal stress (S_{hmax})	Geomechanical tests, wellbore failure modeling, dipole sonic logs
Stress orientation	Orientation of wellbore failure, dipole sonic logs
Pore pressure (P_p)	Pressure monitoring, wireline formation tester
Elastic properties	Core measurements, logs
Faults, fractures	Seismic surveys (2D, 3D, crosswell, and/or microseismic), wellbore imaging (FMI logs)

Meeting the UIC class VI requirements

- Geomechanical risks: a key element of the UIC Class VI regulation

§ 146.82 Required Class VI permit information.

(iv) Geomechanical information on fractures, stress, ductility, rock strength, and in situ fluid pressures within the confining zone(s);

(v) Information on the seismic history including the presence and depth of seismic sources and a determination that the seismicity would not interfere with containment; and

§ 146.84 Area of review and corrective action.

(a) The area of review is the region surrounding the geologic sequestration project where USDWs may be endangered by the injection activity. The area of review is delineated using computational modeling that accounts for the physical and chemical properties of all phases of the injected carbon dioxide stream and is based on available site characterization, monitoring, and operational data.

§ 146.83 Minimum criteria for siting.

(1) An injection zone(s) of sufficient areal extent, thickness, porosity, and permeability to receive the total anticipated volume of the carbon dioxide stream;

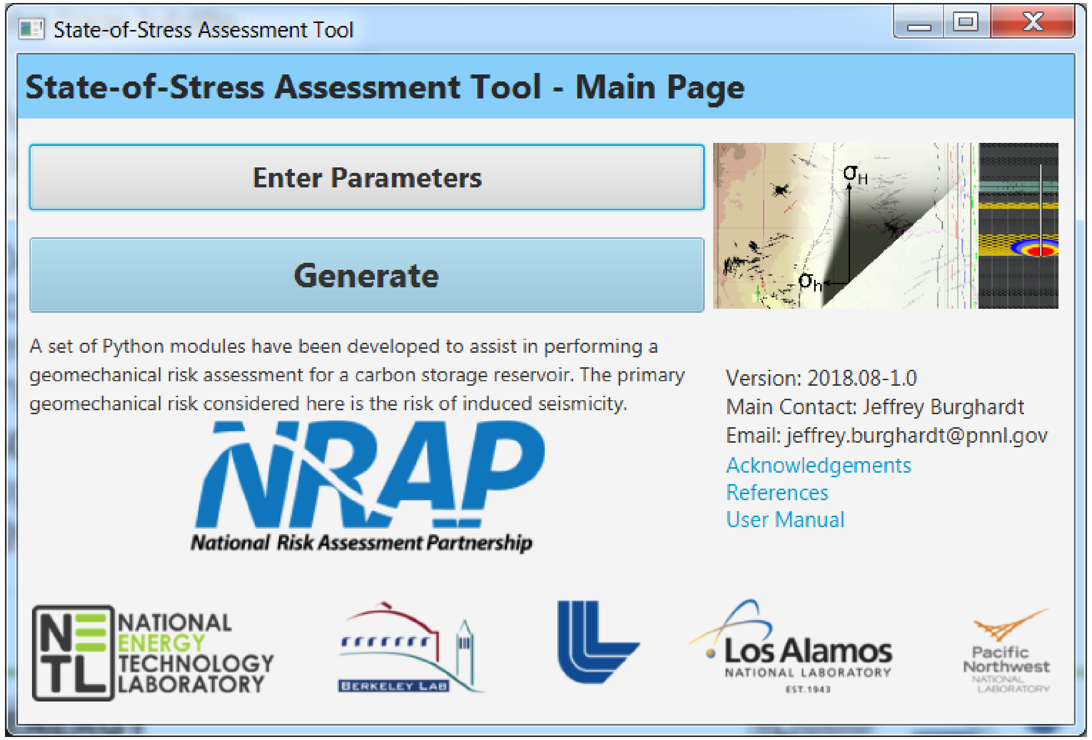
(2) Confining zone(s) free of transmissive faults or fractures and of sufficient areal extent and integrity to contain the injected carbon dioxide stream and displaced formation fluids and allow injection at proposed maximum pressures and volumes without initiating or propagating fractures in the confining zone(s).

§ 146.88 Injection well operating requirements.

(a) Except during stimulation, the owner or operator must ensure that injection pressure does not exceed 90 percent of the fracture pressure of the injection zone(s) so as to ensure that the injection does not initiate new fractures or propagate existing fractures in the injection zone(s). In no case may injection pressure initiate fractures in the confining zone(s) or cause the movement of injection or formation fluids that endangers a USDW. Pursuant

SOSAT: A tool to evaluate the geomechanical risks

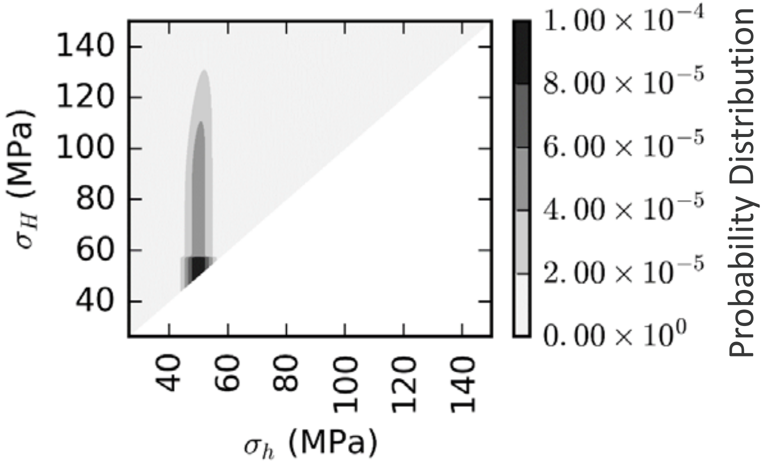
- **Purpose of SOSAT:**
  - To help operators and regulators evaluate the geomechanical risks at a given depth by taking into account uncertainties in the field properties



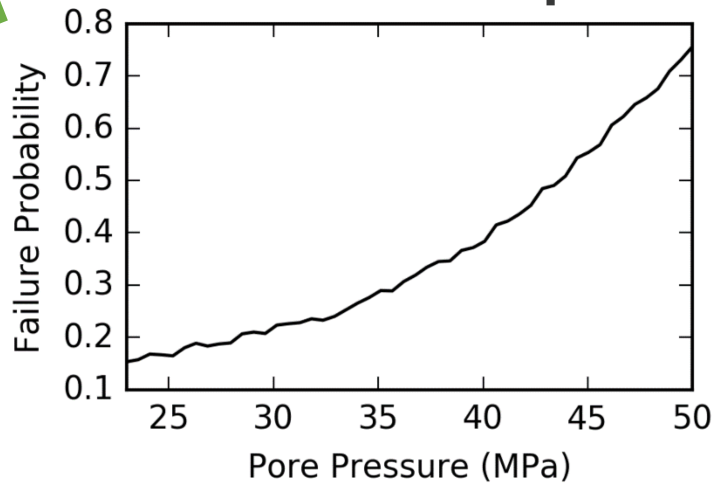
What is SOSAT?

- **SOSAT provides an integrated framework to:**
  - Estimate the probability distribution of the state of stress at a given point
  - Estimate the probability of activating a critically-oriented fault over a range of pore pressure increase
  - account for uncertainties in parameters
- Based on assumption that a critically oriented fault exists (very conservative approach)

Calculated stress probability distribution

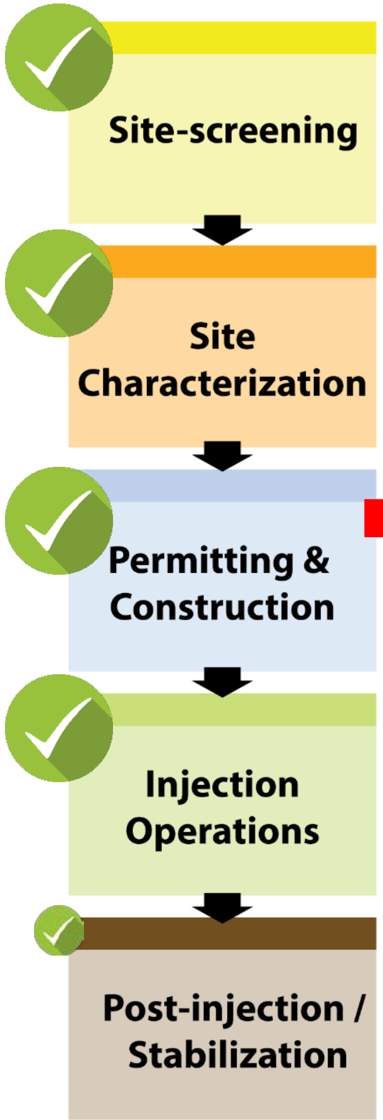


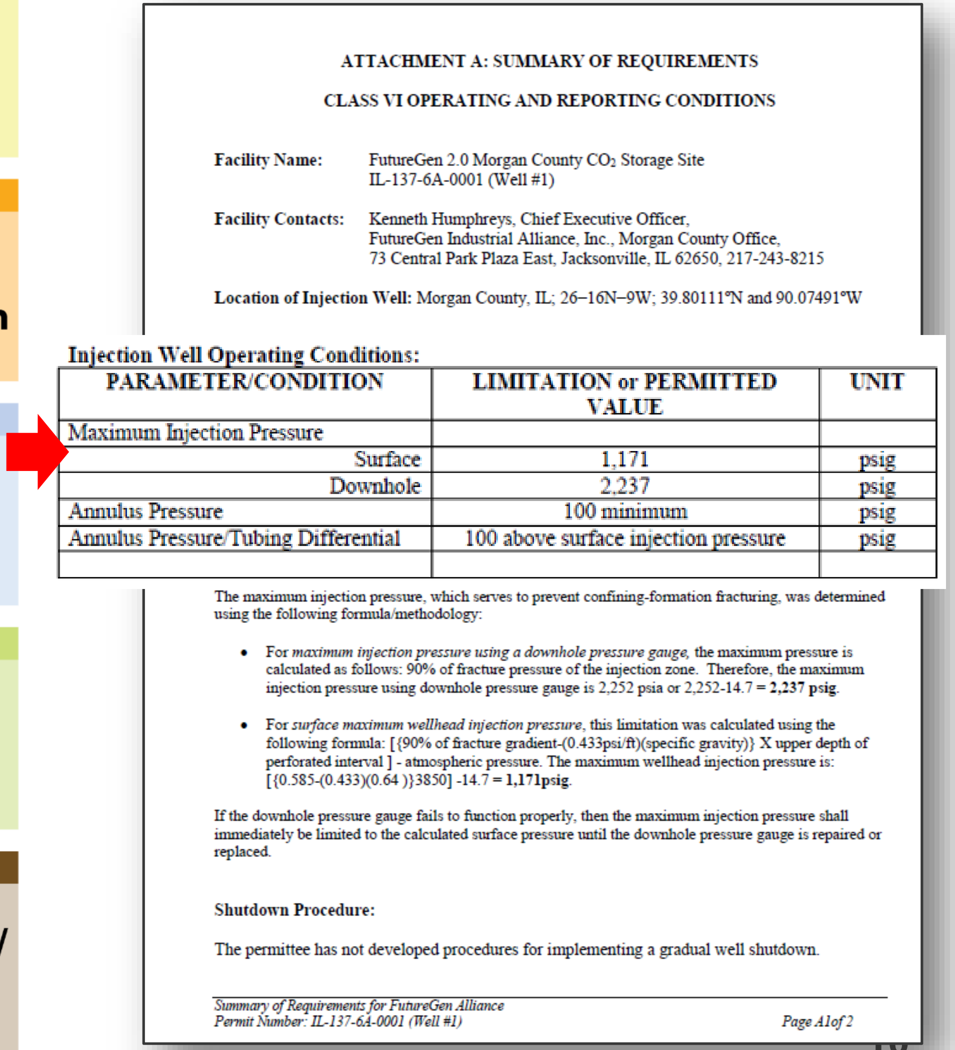
Fault activation probability



When to use SOSAT?

- From site screening to end of injection operations
- To evaluate what type of data are critical to reduce uncertainty in geomechanical risk
- To make informed decisions about operational parameters (i.e., maximum injection pressure allowed)





ATTACHMENT A: SUMMARY OF REQUIREMENTS

CLASS VI OPERATING AND REPORTING CONDITIONS

Facility Name: FutureGen 2.0 Morgan County CO_2 Storage Site
IL-137-6A-0001 (Well #1)

Facility Contacts: Kenneth Humphreys, Chief Executive Officer,
FutureGen Industrial Alliance, Inc., Morgan County Office,
73 Central Park Plaza East, Jacksonville, IL 62650, 217-243-8215

Location of Injection Well: Morgan County, IL; 26–16N–9W; 39.80111°N and 90.07491°W

Injection Well Operating Conditions:

PARAMETER/CONDITION	LIMITATION or PERMITTED VALUE	UNIT
Maximum Injection Pressure		
Surface	1,171	psig
Downhole	2,237	psig
Annulus Pressure	100 minimum	psig
Annulus Pressure/Tubing Differential	100 above surface injection pressure	psig

The maximum injection pressure, which serves to prevent confining-formation fracturing, was determined using the following formula/methodology:

- For *maximum injection pressure using a downhole pressure gauge,* the maximum pressure is calculated as follows: 90% of fracture pressure of the injection zone. Therefore, the maximum injection pressure using downhole pressure gauge is 2,252 psia or 2,252-14.7 = **2,237 psig**.
- For *surface maximum wellhead injection pressure*, this limitation was calculated using the following formula: [{90% of fracture gradient-(0.433psi/ft)(specific gravity)} X upper depth of perforated interval] - atmospheric pressure. The maximum wellhead injection pressure is: [{0.585-(0.433)(0.64)}3850] -14.7 = **1,171psig**.

If the downhole pressure gauge fails to function properly, then the maximum injection pressure shall immediately be limited to the calculated surface pressure until the downhole pressure gauge is repaired or replaced.

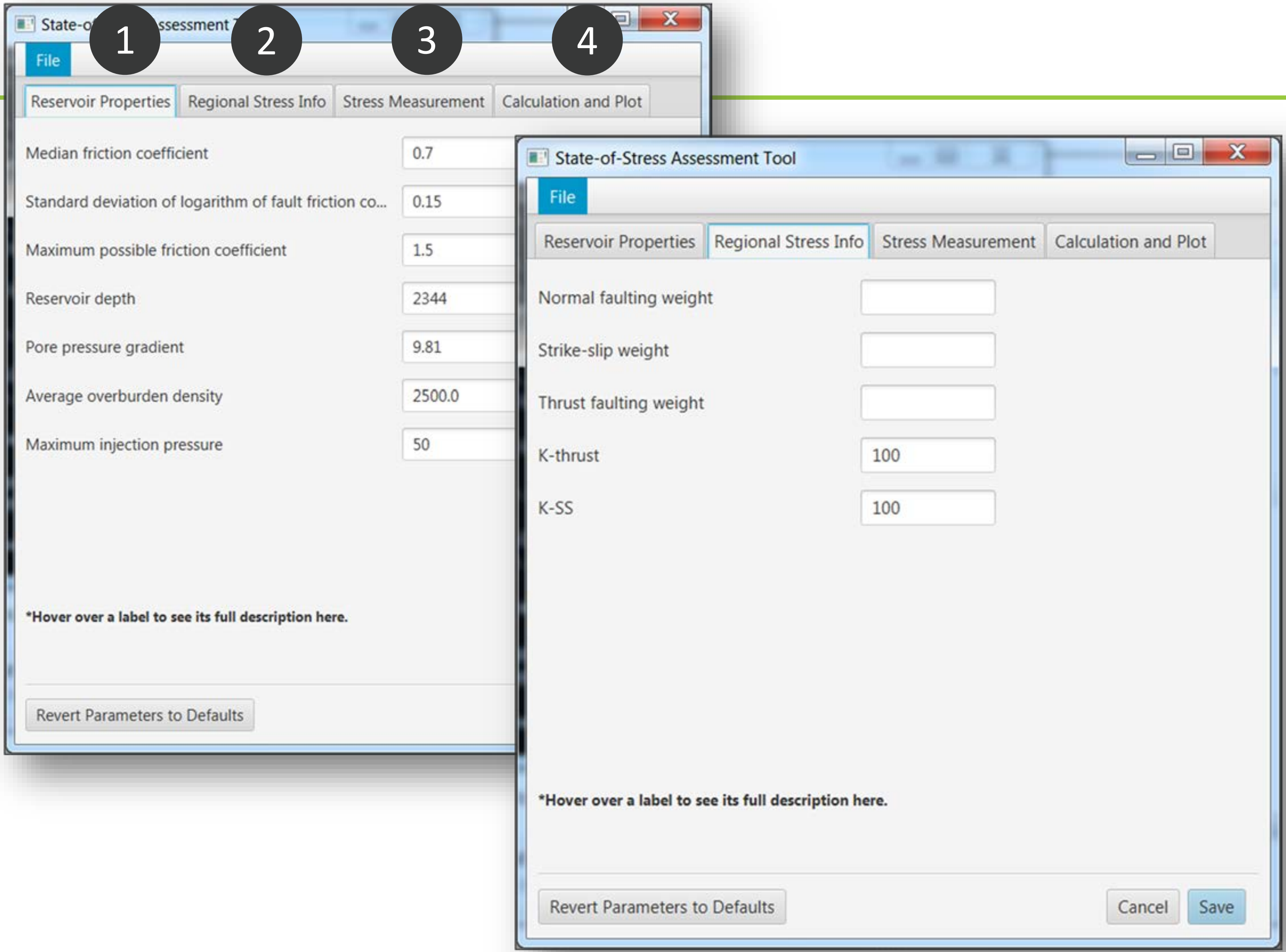
Shutdown Procedure:

The permittee has not developed procedures for implementing a gradual well shutdown.

Summary of Requirements for FutureGen Alliance
Permit Number: IL-137-6A-0001 (Well #1) *Page A1of 2*

How to use SOSAT?

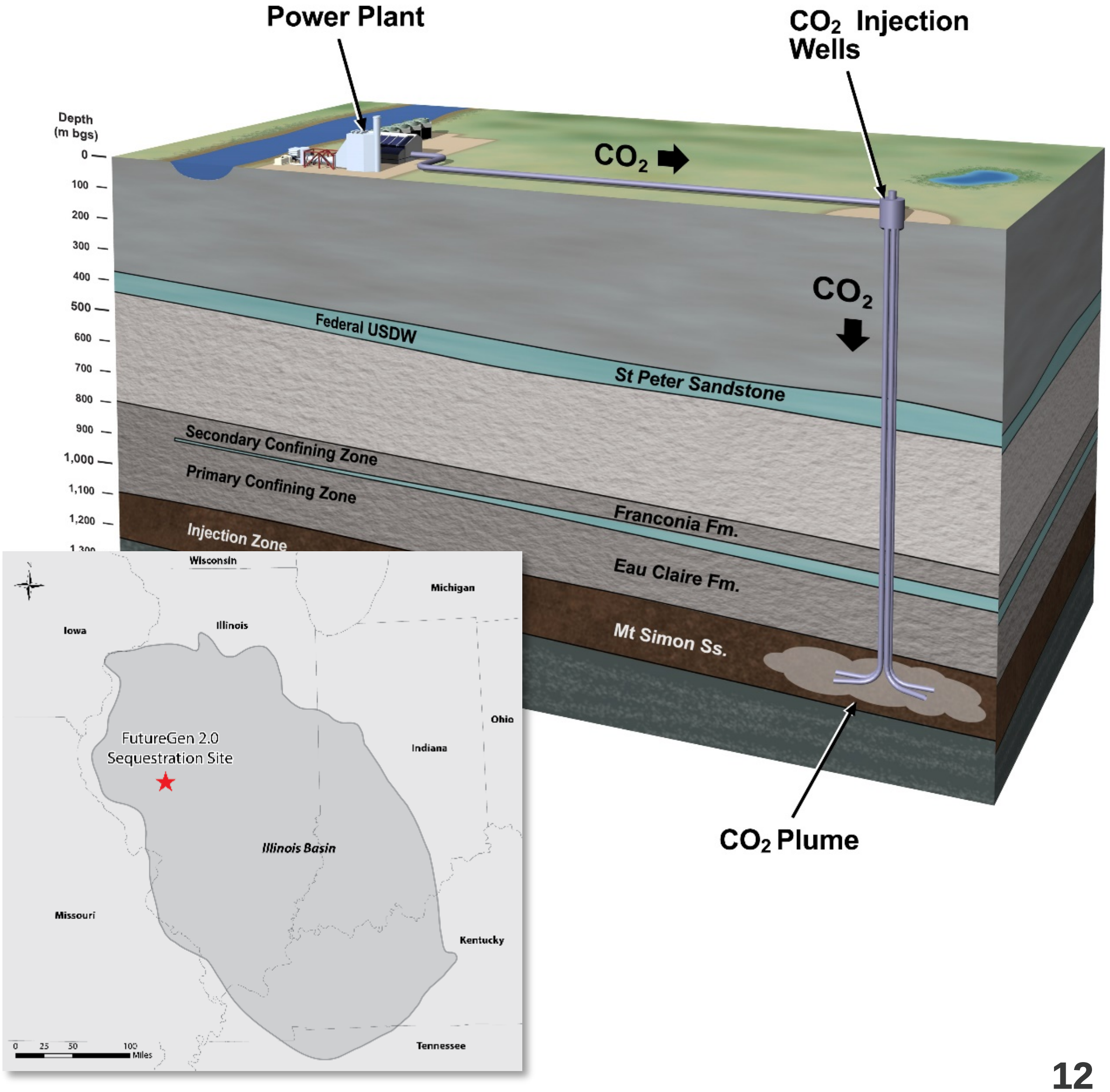
Parameters required by SOSAT
Reservoir depth
Reservoir pore pressure
Density of overburden
Regional tectonic regime
Reservoir rock mechanical properties
Stress measurements (S_{hmin})



- Application of SOSAT to FutureGen 2.0: revisiting the first UIC class VI permit issued

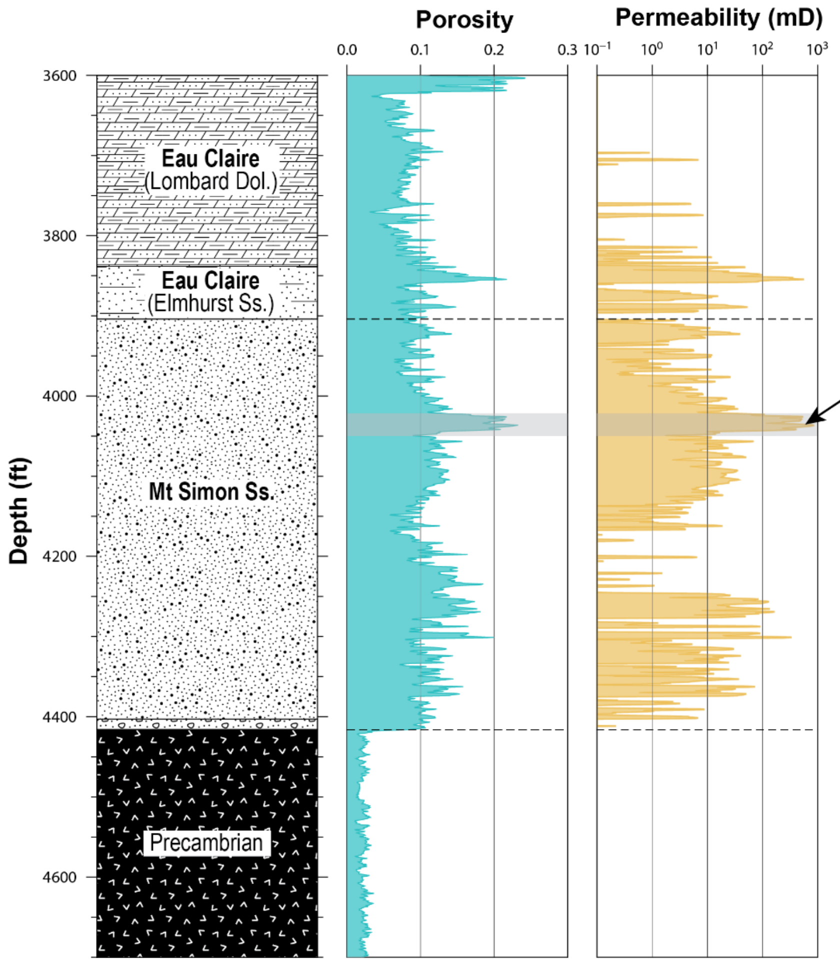
Overview of the FutureGen 2.0 Project

- 1.1 MMT/year for 20 years (22 Mt) injected into the Mount Simon Formation
- First-ever UIC class VI permits issued in the U.S.
- Project cancelled in 2015
- Extensive characterization and modeling efforts
- Used as a reference case to test NRAP tools



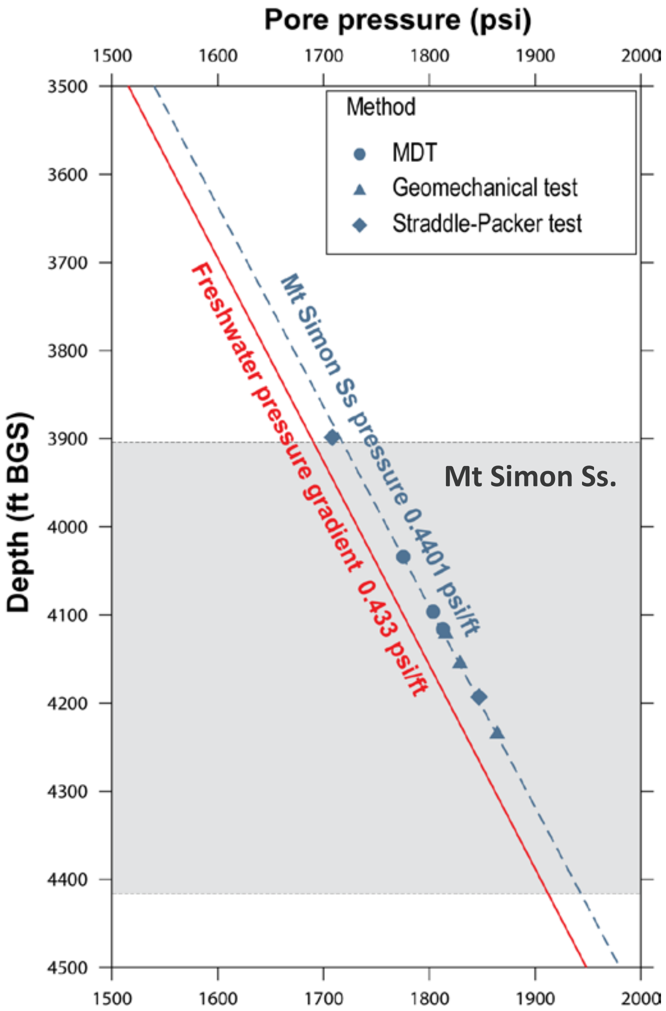
FutureGen 2.0 reservoir properties (1)

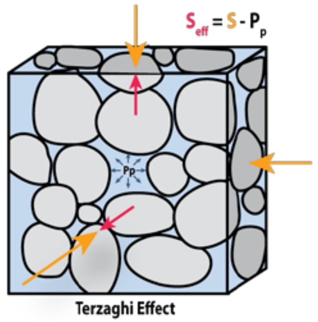
Reservoir depth



4,030 ft
(1228 m)

Pore pressure gradient

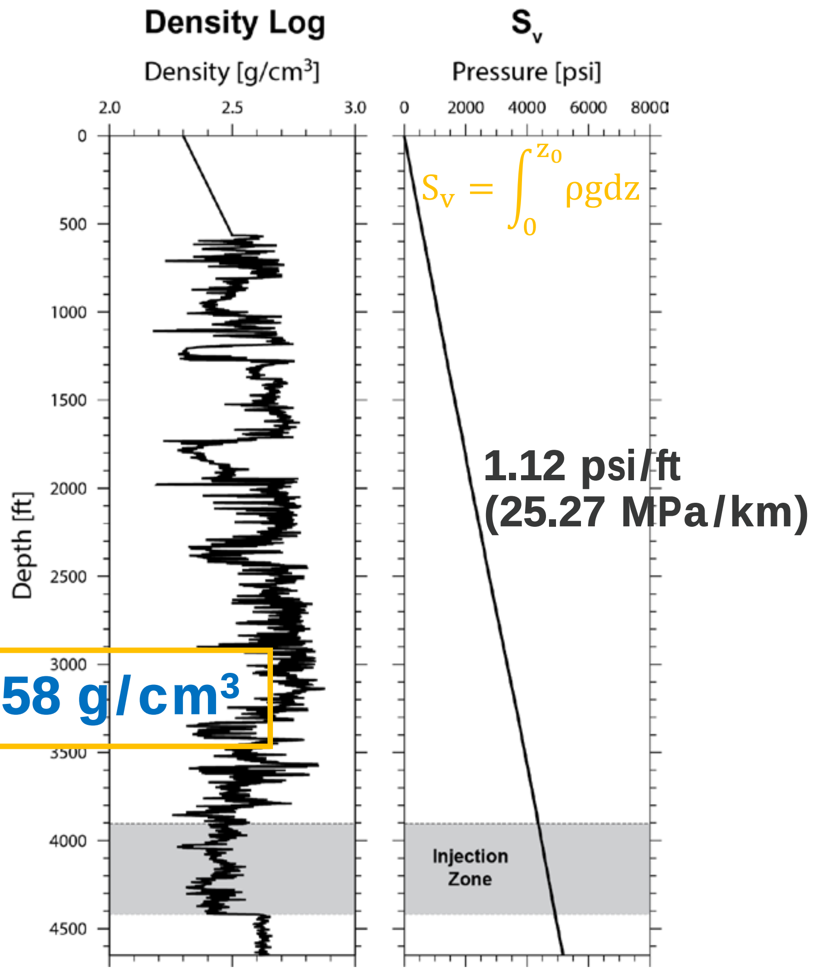




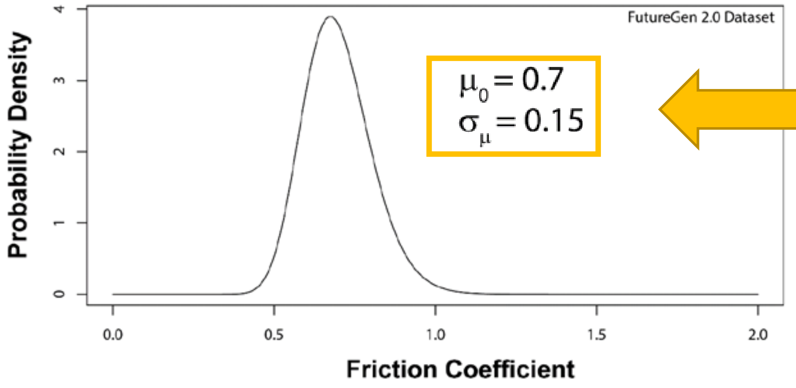
Pore pressure gradient = 0.440 psi/ft
(9.96 MPa/km)

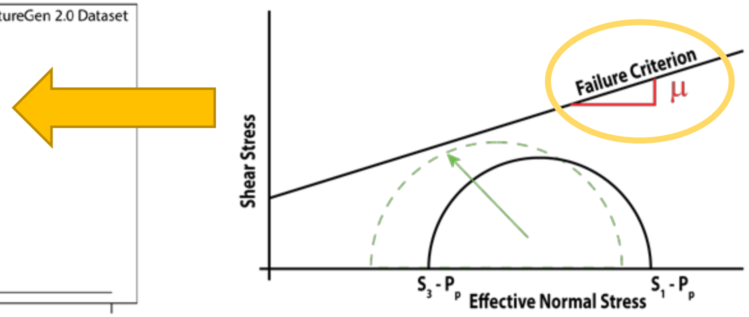
FutureGen 2.0 reservoir properties (2)

Average overburden density



Lognormal distribution of friction coefficient





Injection pressure

40 CFR 146.88(a): *"Operator must ensure that injection pressure does not exceed 90% of the fracture pressure of the injection zone".*

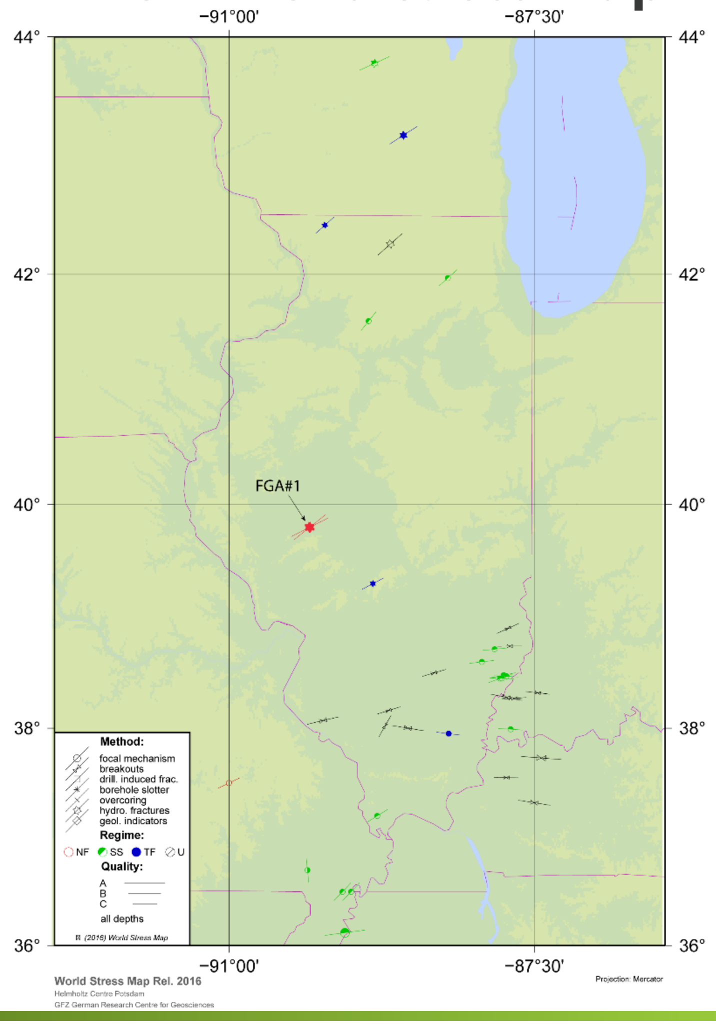
$$P_{max} = 0.65 * 0.9 * z_{inj}$$

P_{max} at 4,030 ft is 2358 psi (16.23 MPa)

Regional stress observations

Regional stress observations from World Stress Map

a)

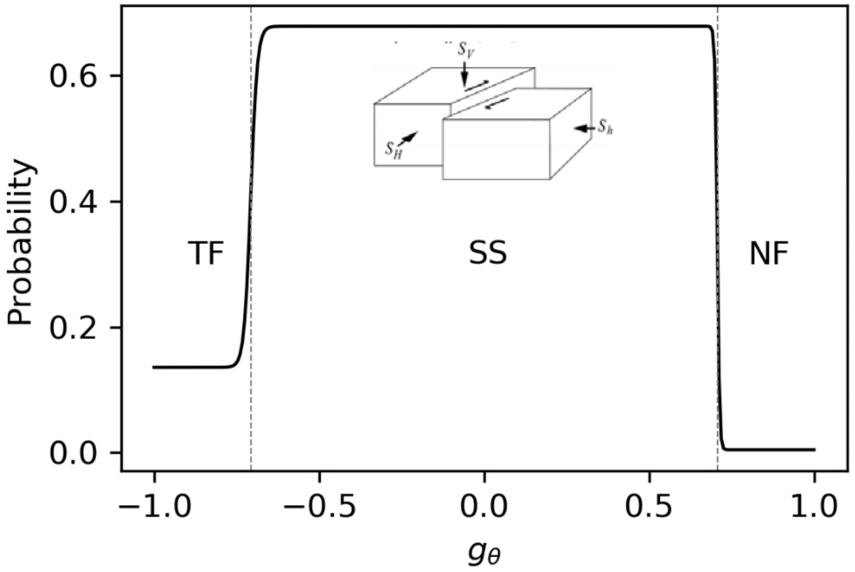


- Regional observations(HF measurements) indicate a strike-slip faulting regime

$$S_{Hmax} > S_v > S_{hmin}$$

- S_{hmin} may reach values close to S_v (SS→TF)

Probability distribution of the regional stress state

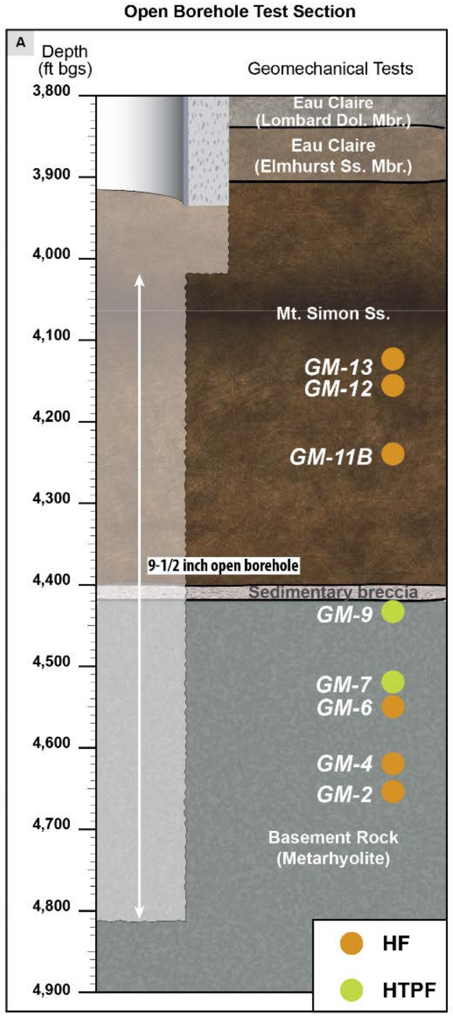


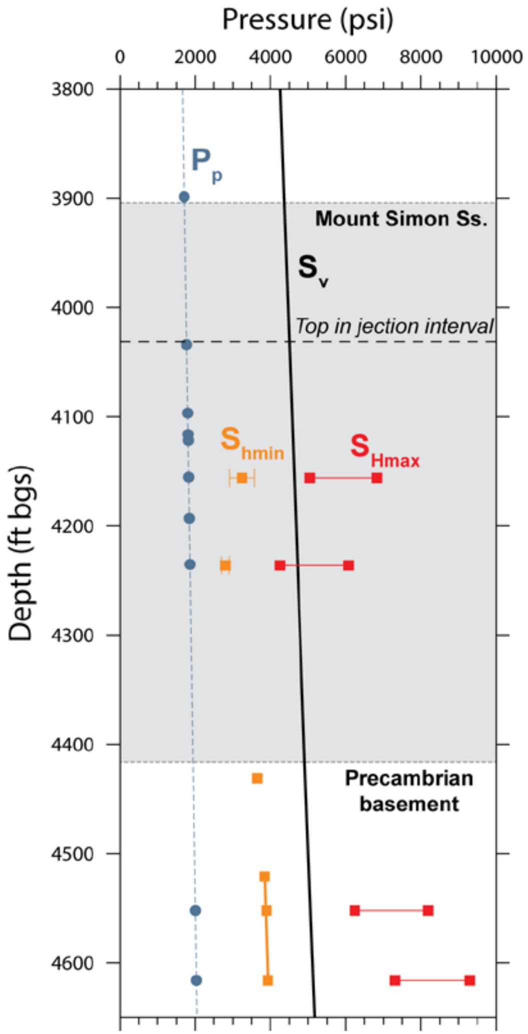
TF = thrust faulting (reverse)
SS = strike-slip
NF = normal faulting

FutureGen 2.0 In-Situ Stress Measurements

- Two reliable estimate for S_{hmin} obtained in the Mount Simon Ss.
- These two measurements represent the bounding values of S_{hmin}
- Strike-slip stress faulting regime:

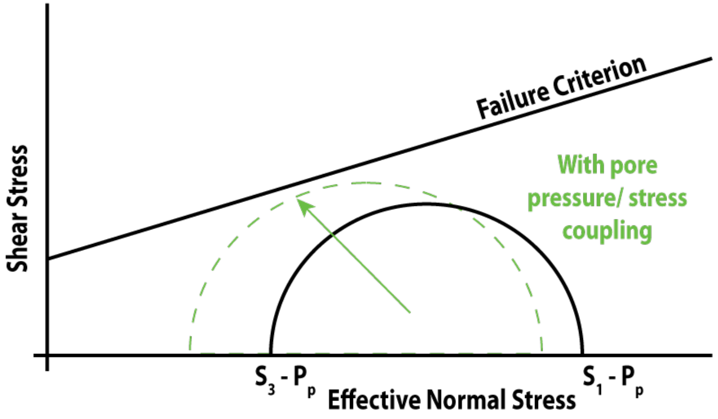
$$S_{Hmax} > S_v > S_{hmin}$$



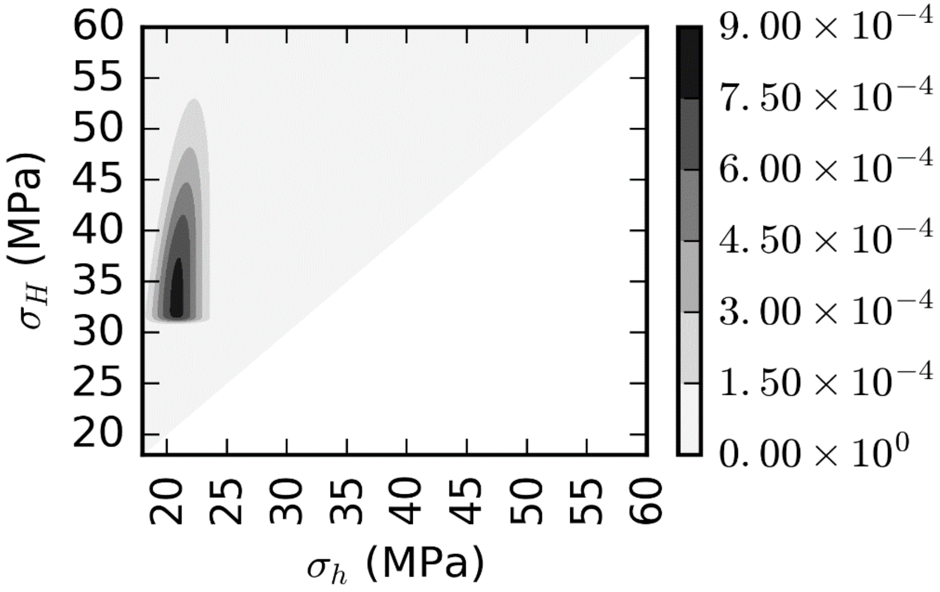


Reservoir Stress Path

- Horizontal stresses evolve as pore pressure increases
- Limited data on elastic properties (3 triaxial tests on core samples from Mount Simon Ss.)
- SOSAT input: $0.4 < \Gamma_h < 0.6$
- Total horizontal stresses are expected to increase by 40 to 60% of the increase in pore pressure

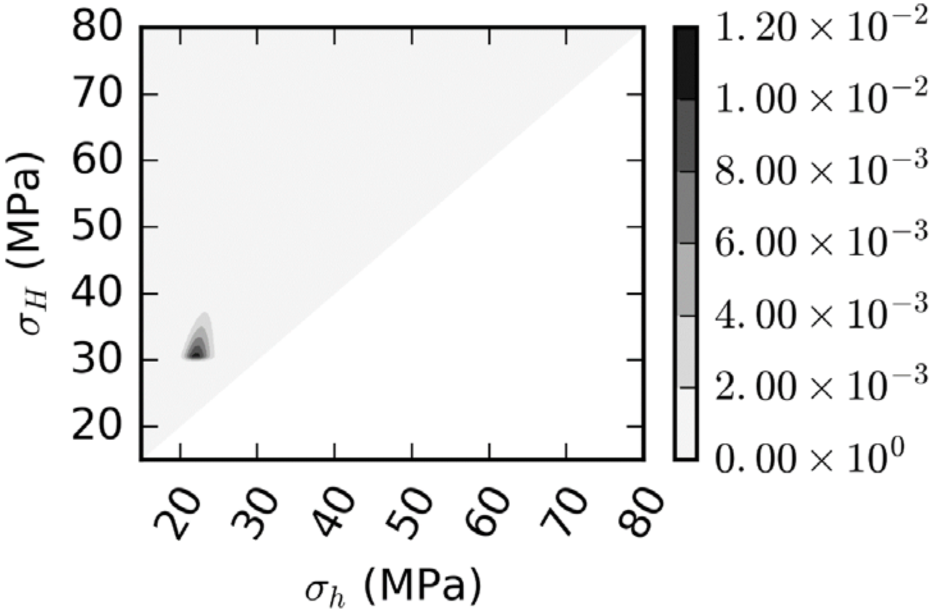


Results: Posterior Stress Distribution



- S_{hmin} well constrained
- Uncertainty on S_{hmax}

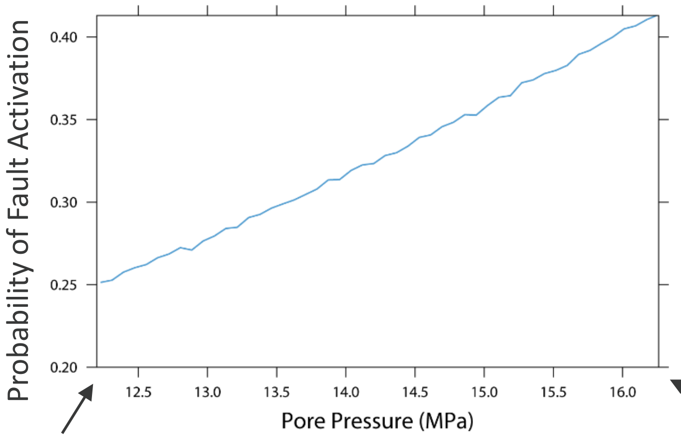
New feature: incorporating Breakouts and Drilling induced tensile fractures (DITF) analysis



- Absence of breakouts or DITF excludes very high values of σ_H (S_{Hmax})
- Data needed: mud weight, rock strength, mud temperature, etc.

Risk of induced shear failure on a critically oriented fault

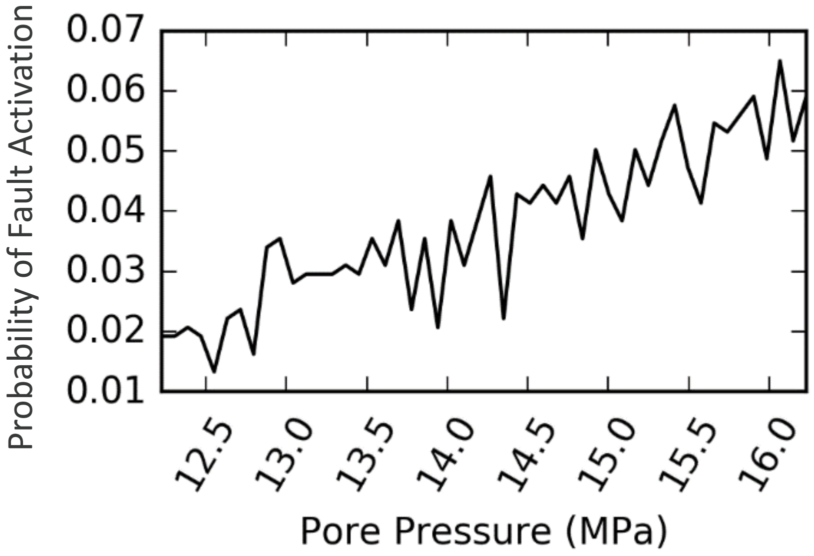
- The probability that the Mount Simon reservoir is initially critically **stressed is relatively high (25%)**
- When the pore pressure increases to max. injection pressure, **probability reaches 43%.**
- Based on assumption that a critically oriented fault exists but no such fault has been identified at the FutureGen 2.0 site



Initial pore pressure

Max. P_{inj}

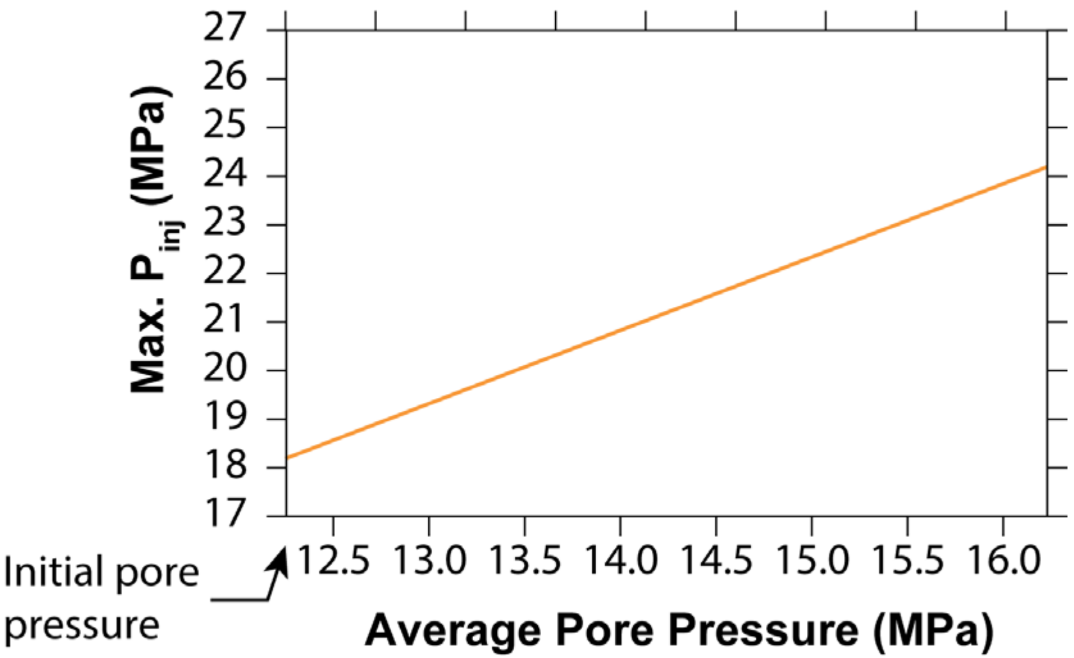
- With new feature (currently being tested)
  - The probability that the Mount Simon reservoir is initially **critically stressed is low (2%)**
  - When the pore pressure increases to max. injection pressure, **probability reaches 6%.**
  - **Fault reactivation is not a major risk**



Risk of unintentional hydraulic fracturing

Getting further

- Maximum allowable pressure under initial conditions = 18.2 MPa (permitted:16.23 MPa)
- Once pore pressure increases in the reservoir, the injection pressure can be increased while maintaining the same probability of inducing hydraulic fracturing.
- **Risk of hydraulic fracturing is very limited**



Injection pressure that would produce a 1%, probability of hydraulic fracturing as a function of reservoir pore pressure.

User Feedback & Conclusions (1)

- **Application to FutureGen 2.0:**
  - Confirms the validity of max. injection pressure allowed by the UIC Class VI permit
  - Some data were missing to build a comprehensive geomechanical model and reduce uncertainties.
  - Importance to know the critical data for proper planning (characterization plan)

User Feedback & Conclusions (2)

- SOSAT:
  - Geomechanical risks can be evaluated
  - Gaps for characterization data can easily be identified
  - User-friendly interface, flexibility with units and parameters
  - Users: SMEs (geologists / geoscientists with background in geomechanics)
  - Additional features currently being tested to reduce uncertainties (breakouts and drilling induced tensile fractures analysis)

ORIGINAL PAPER

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Geomechanical Risk Assessment for Subsurface Fluid Disposal Operations

J. Burghardt[1]

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Abstract
Numerical models are commonly used to estimate the state of stress in the subsurface for various engineering applications. These estimates are subject to considerable uncertainty, and yet, the estimates are almost always deterministic, yielding no information about the certainty of the prediction. For some applications, unquantified uncertainties in stress are often acceptable, because the risks related to geomechanics may be of low relative importance compared to other risks (e.g., recoverable resource volume), for which uncertainties are often quantified. Furthermore, many geomechanics-related risks in the petroleum industry are relatively short-lived (e.g., well bore stability) and decrease in importance with time. In contrast, for wastewater injection or geologic carbon sequestration (GCS), geomechanics-related risks (e.g., seal integrity, induced seismicity) are on par with resource-related risks and are of long-term concern, with the risk generally increasing in importance for a significant period of time. For these reasons, the deterministic stress estimation and risk analysis approaches generally applied in the petroleum industry are insufficient for GCS applications. This paper describes a Bayesian approach to geomechanical uncertainty quantification and risk assessment. The method is demonstrated using data from an active enhanced oil recovery/geologic carbon sequestration field as a case study.

Keywords Uncertainty quantification · Stress estimation · Waste injection · Induced seismicity · Risk analysis

List of symbols

Π	Probability density function
Π_o	Homogeneous probability density function
σ_i	The components of the Cauchy stress tensor expressed in 6-D (Mandel) space
$\bar{\sigma}_i$	The components of the Cauchy stress tensor expressed in 6-D (Voigt) space
σ_V	Total vertical stress
σ_H	Total maximum horizontal stress
σ_h	Total minimum horizontal stress
τ_{HV}	Maximum horizontal–vertical shear stress
τ_{hV}	Minimum horizontal–vertical shear stress
τ_{hH}	Horizontal shear stress
σ_1	Largest total principal stress
σ_2	Intermediate total principal stress
σ_3	Smallest total principal stress
$\bar{\sigma}_V$	Vertical Terzaghi effective stress
$\bar{\sigma}_H$	Maximum horizontal Terzaghi effective stress
$\bar{\sigma}_h$	Minimum horizontal Terzaghi effective stress
p	Mean stress
q	Equivalent shear stress
P_p	Pore fluid pressure
x_V	Spatial coordinate in the vertical direction
x_H	Spatial coordinate in the direction of the maximum horizontal stress direction
u_V	Displacement in the vertical direction
u_H	Displacement in the direction of the maximum horizontal principal stress
ε_i	The components of the infinitesimal strain tensor expressed in 6-D (Mandel) space
$\bar{\varepsilon}_i$	The components of the Infinitesimal strain tensor expressed in 6-D (Voigt) space
ε_V	Vertical strain
ε_H	Maximum horizontal strain
ε_h	Minimum horizontal strain
γ_{HV}	Maximum horizontal–vertical shear strain (tensorial)
γ_{hV}	Minimum horizontal–vertical shear strain (tensorial)
γ_{hH}	Horizontal shear strain (tensorial)
C_{ijkl}	Components of fourth-order linear elastic stiffness tensor
C_{ij}	Components of elastic stiffness tensor expressed in 6-D (Mandel) space

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