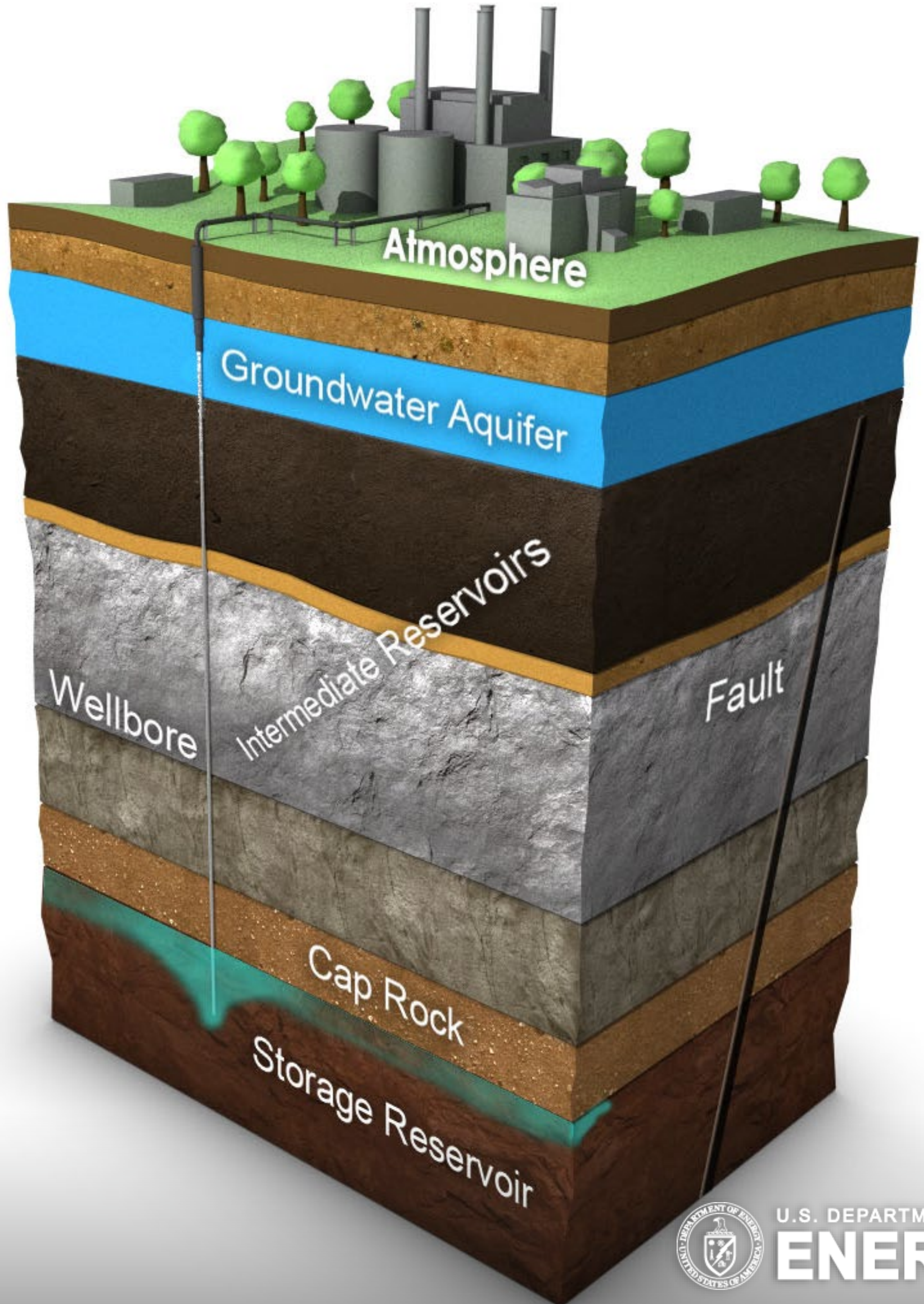
NRAP Task 3 - Induced Seismicity Risk Management

Kayla Kroll, Christopher Sherman, Gina Geffers, Chaoyi Wang (LLNL); Jeff Burghardt, Delphine Appriou, Wenjing Wang, Ryan Haagenson (PNNL); Yves Gugliemi, Jonny Rutqvist, Corinne Layland-Bachman (LBNL); Ting Chen (LANL)

FECM/NETL Carbon Management Research Project Review Meeting
Thursday, August 8, 2023

NRAP National Risk Assessment Partnership

NATIONAL ENERGY TECHNOLOGY LABORATORY | Berkeley Lab | Los Alamos National Laboratory | Pacific Northwest National Laboratory



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Project Overview

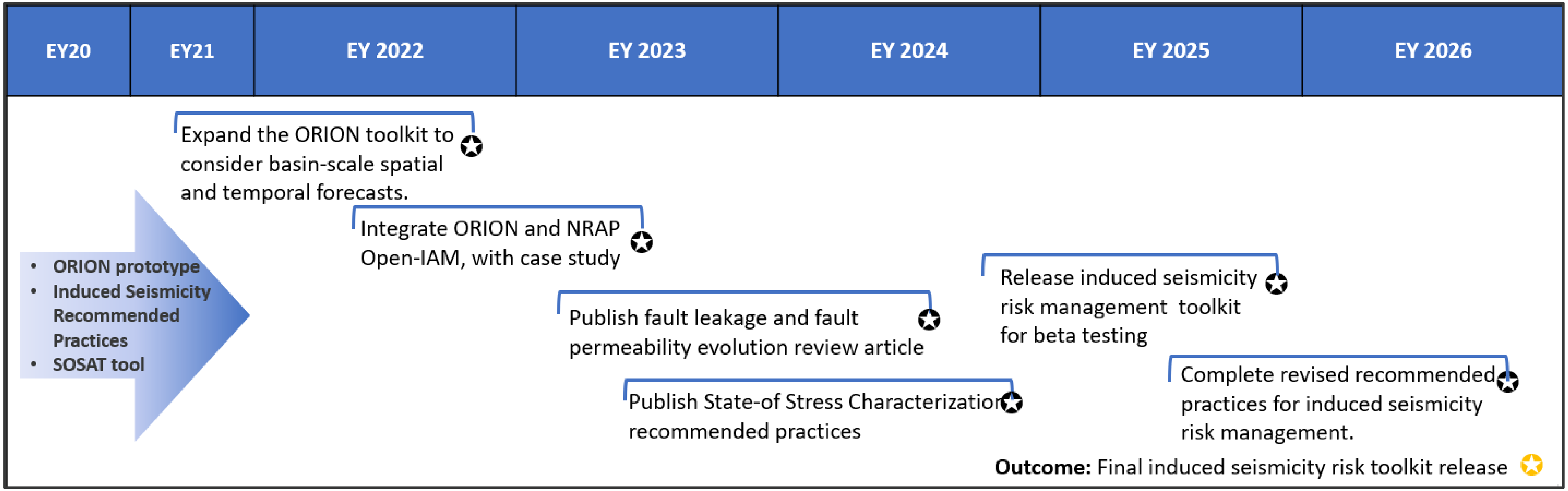
Key Project participants

LLNL	PNNL	LBNL	LANL
• Kayla Kroll • Chris Sherman • Gina Geffers • Chaoyi Wang	• Jeff Burghardt • Wenjing Wang • Delphine Appriou	• Yves Gugliemi • Jonny Rutqvist • Corinne Layland-Bachmann	• Ting Chen

Task 3.0: Induced Seismicity Risk Management

EY24-Q1 BIL-NRAP (Phase 3) Quarterly Progress Report, April 1–June 30, 2024

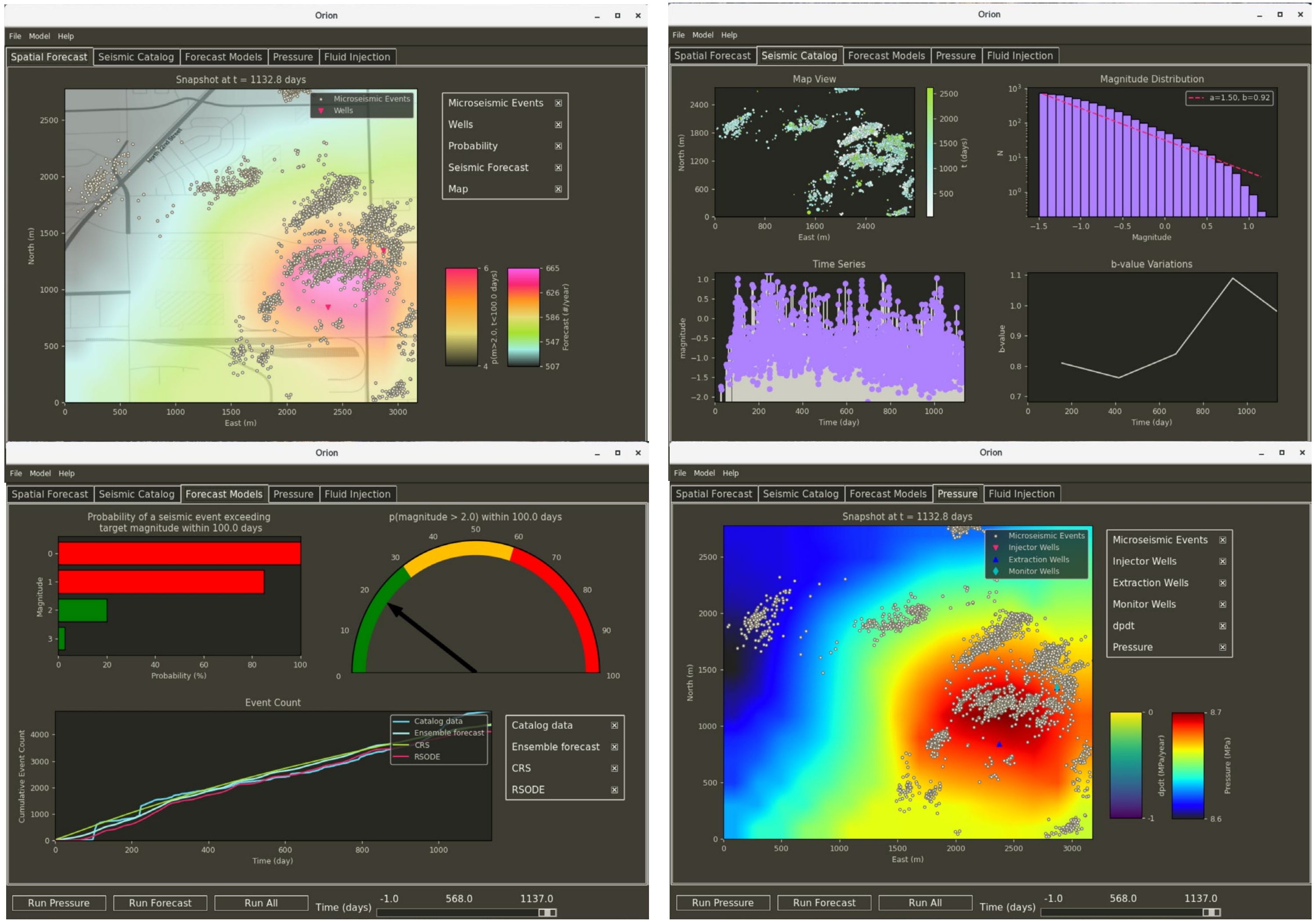
Objective: To refine practical methods and tools to assess and manage induced seismicity risk associated with geologic carbon storage.
To more explicitly link state-of-stress, hydraulic fracturing, potential fault activation and fault leakage risk with integrated risk assessment models.



Basin Scale Spatio-temporal Forecasts

Subtask 3.1: ORION: Operational Forecasting of Induced Seismicity toolkit (Kayla Kroll, Chris Sherman, and Gina Geffers, LLNL)

- Import:
  - Well locations
  - Injection rates
  - Reservoir properties
  - Seismicity catalog
- Compute reservoir pressure and Coulomb stress changes
- Compute spatial and temporal seismicity forecast (via physics and statistical models)



Seismogenic Index Forecasting Model

- Statistical model defined by seismotectonic features of a region (Langenbruch et al., 2018)

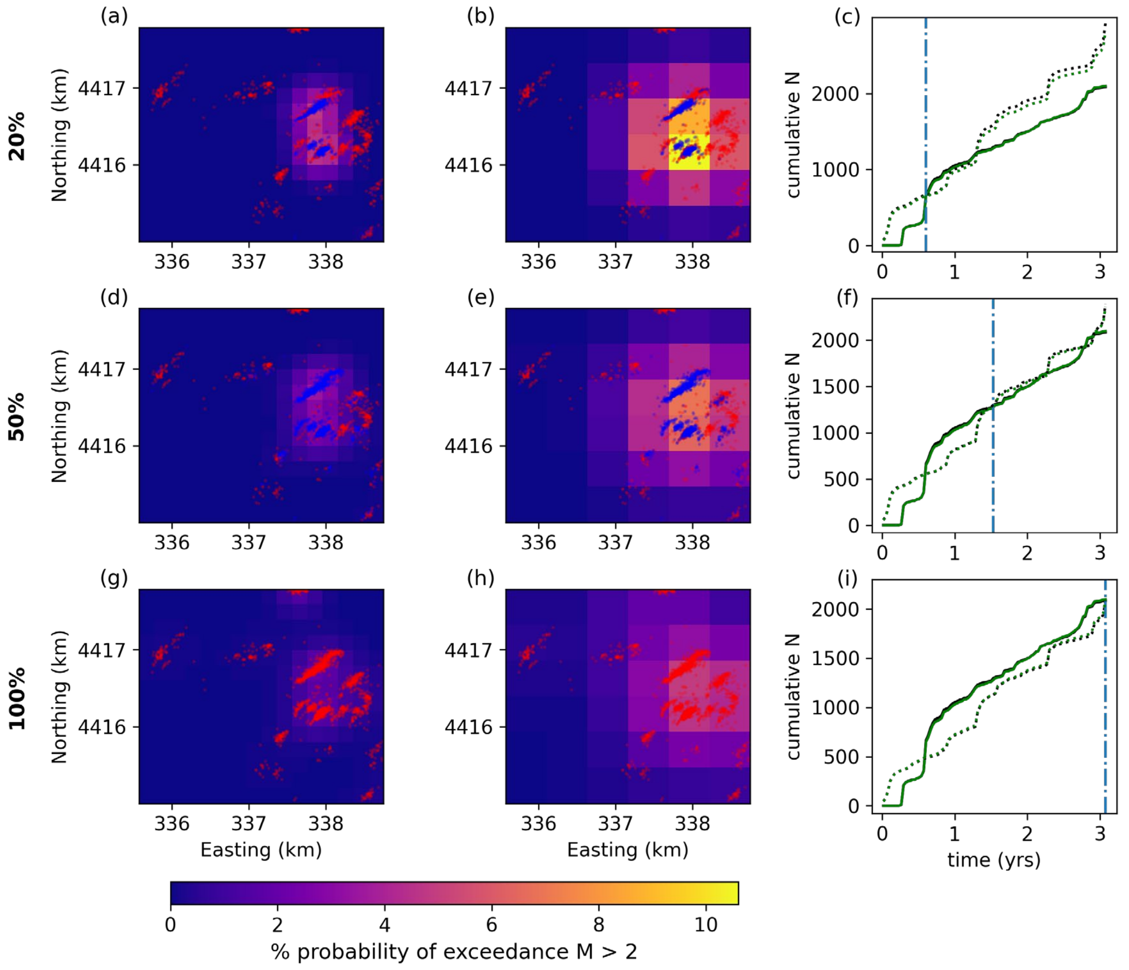
$$\dot{S} = \dot{\tau} - \mu(\dot{\sigma} - \dot{p})$$

$\dot{p}$ = pressurization rate during injection

$\dot{p} = 0$ prior to injection

$$SI = log_{10}N - log_{10}\sum \dot{S}^2 + bM$$

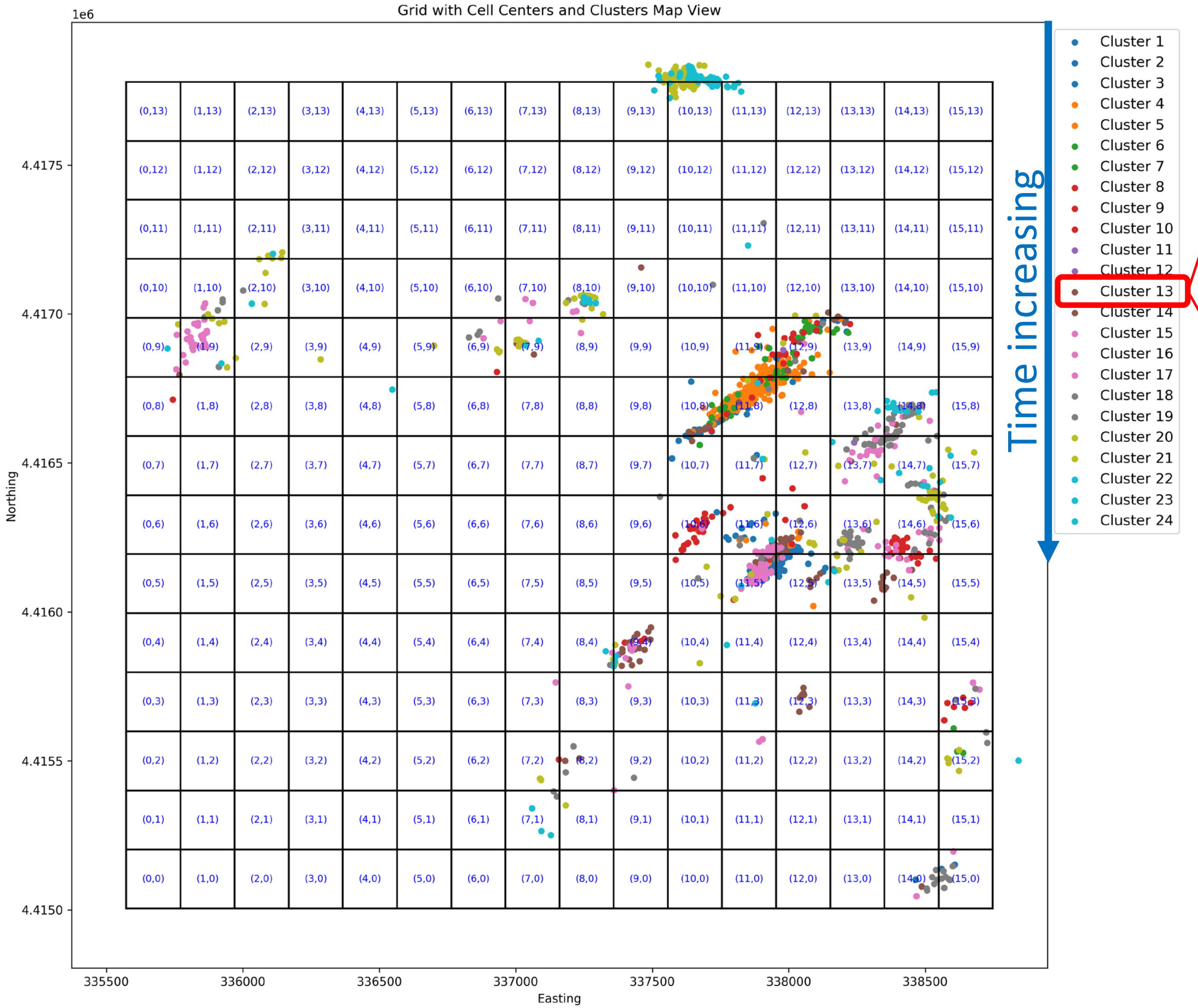
$$R = \dot{S}^2 10^{SI-bM}$$



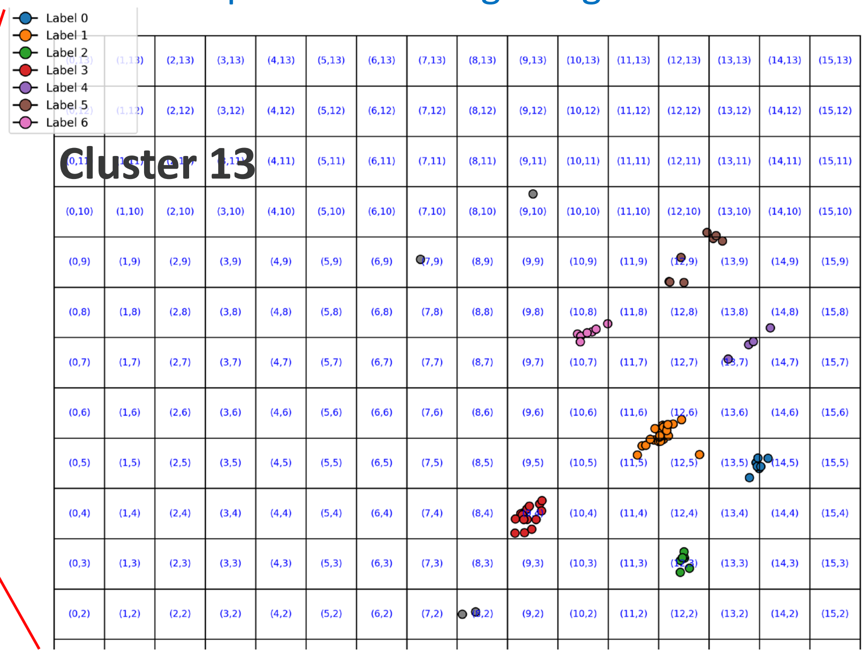
Submitted manuscript, April 2024:
Geffers, G-M., K. A. Kroll, C. S. Sheman, C. Wang. Towards operational forecasting using the seismogenic index model for CO2 storage, SRL

Spatial-temporal clustering at IBDP site

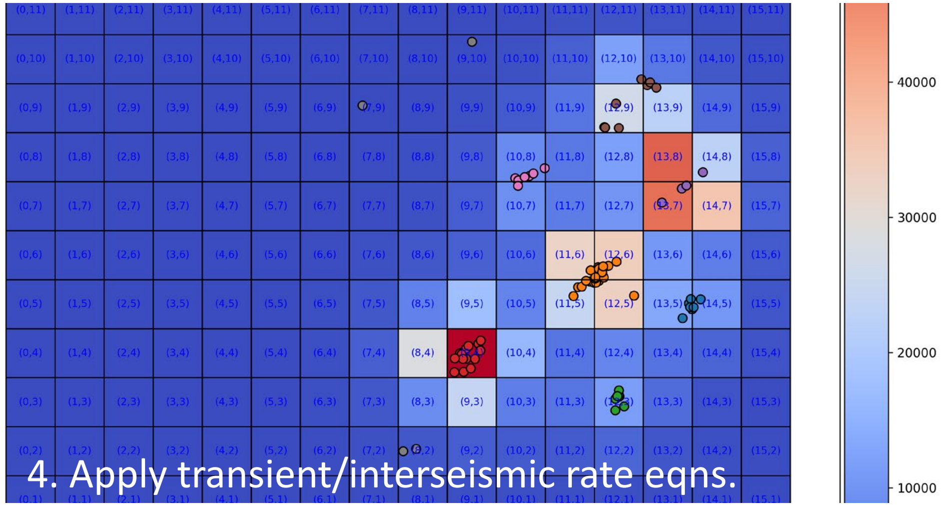
1. Auto temporal clustering using rate density



2. Auto spatial clustering using HDBSCAN



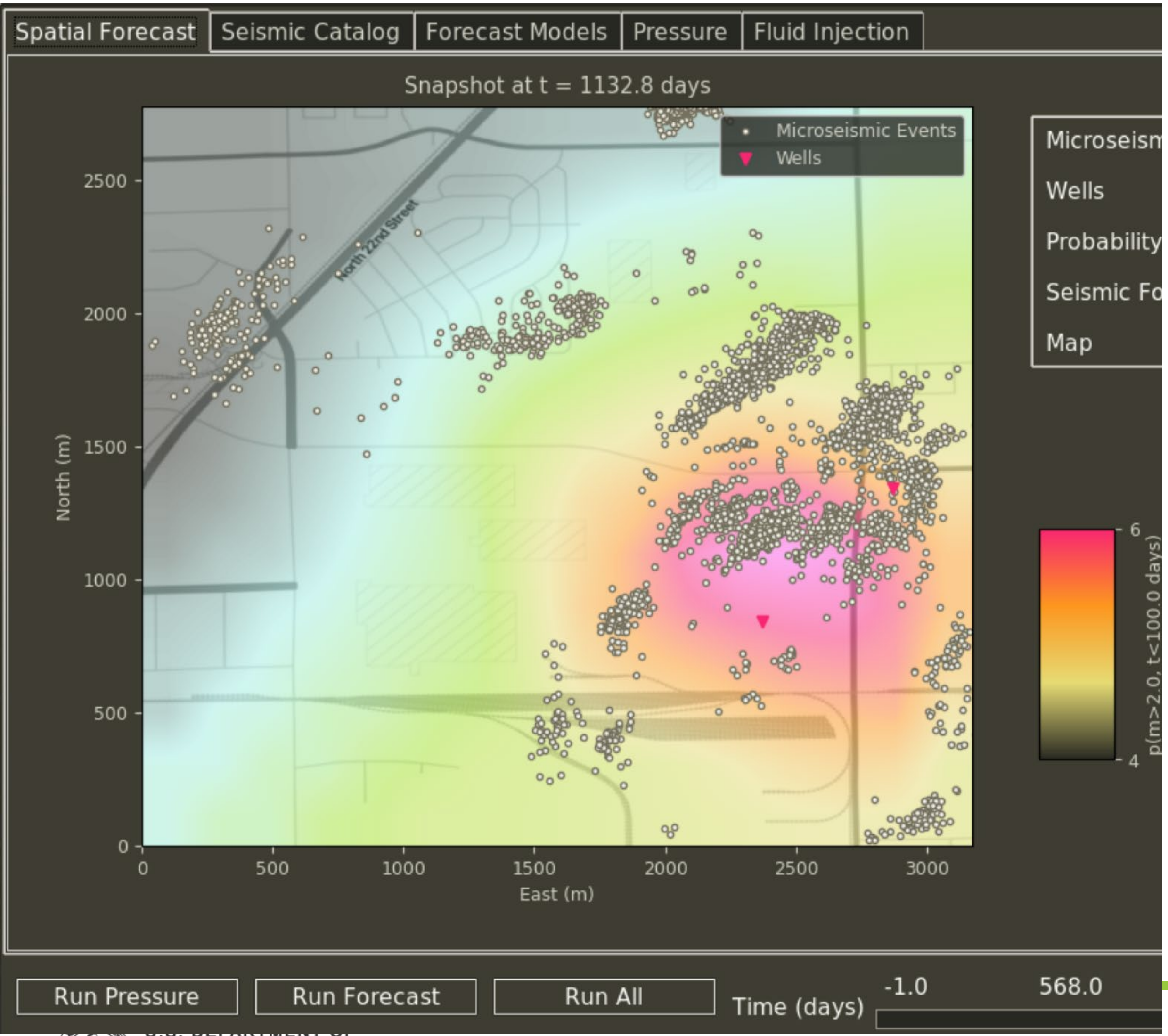
3. Calculate Coulomb stress change



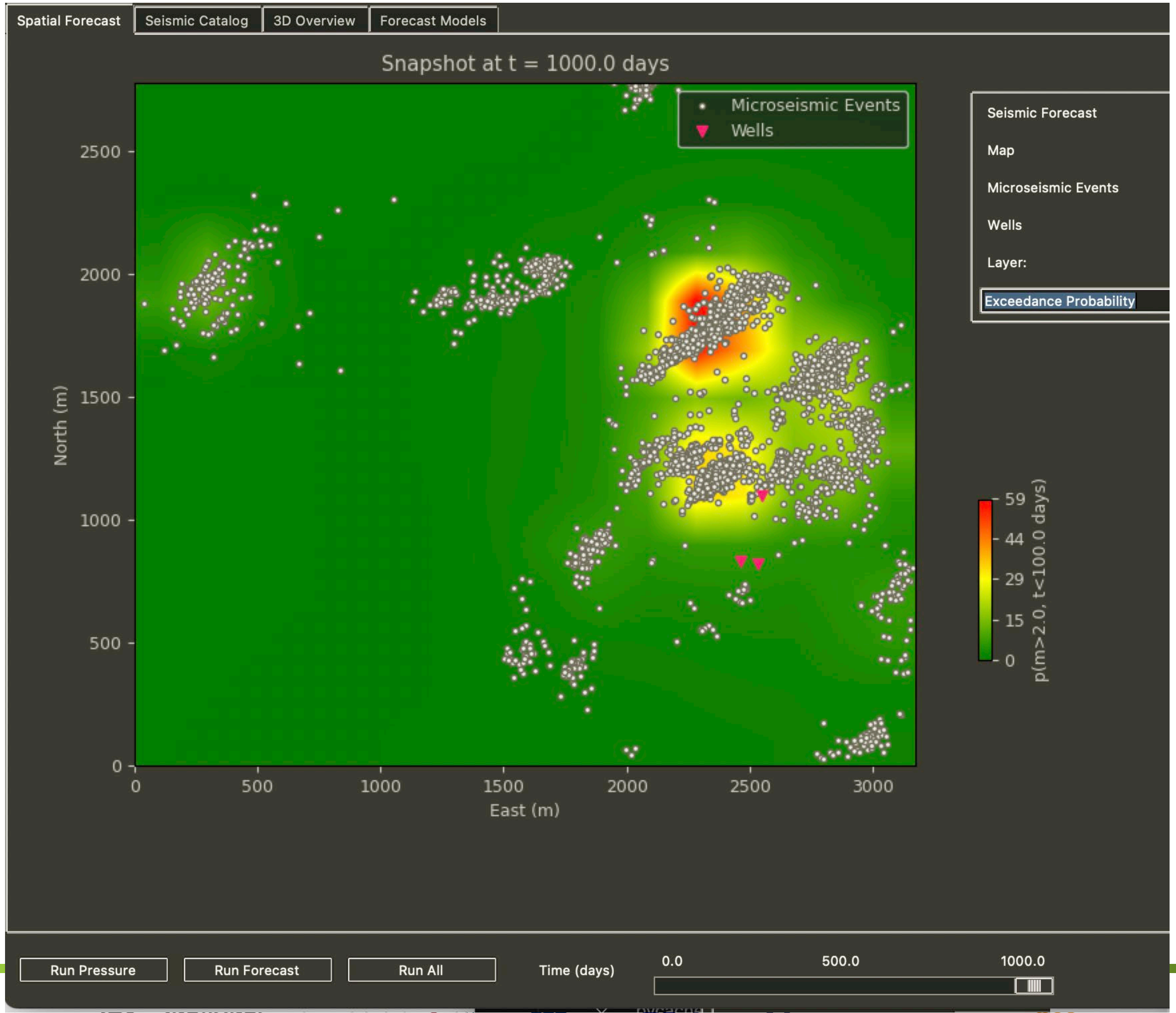
4. Apply transient/interseismic rate eqns.

CRS model in action: Forecast using ORION for IBDP

Forecast without secondary triggering



Forecast with secondary triggering



Basin Scale Spatio-temporal Forecasts

Subtask 3.1: Assessment of operational management strategies (Kayla Kroll, LLNL, Elizabeth Cochran, USGS

High-Fidelity Simulations of Induced Earthquakes to Inform Operational Management Strategies

Kayla A. Kroll[1], Elizabeth S. Cochran[2] and Christopher S. Sherman[1]
kroll5@llnl.gov; ecochran@usgs.gov; sherman27@llnl.gov

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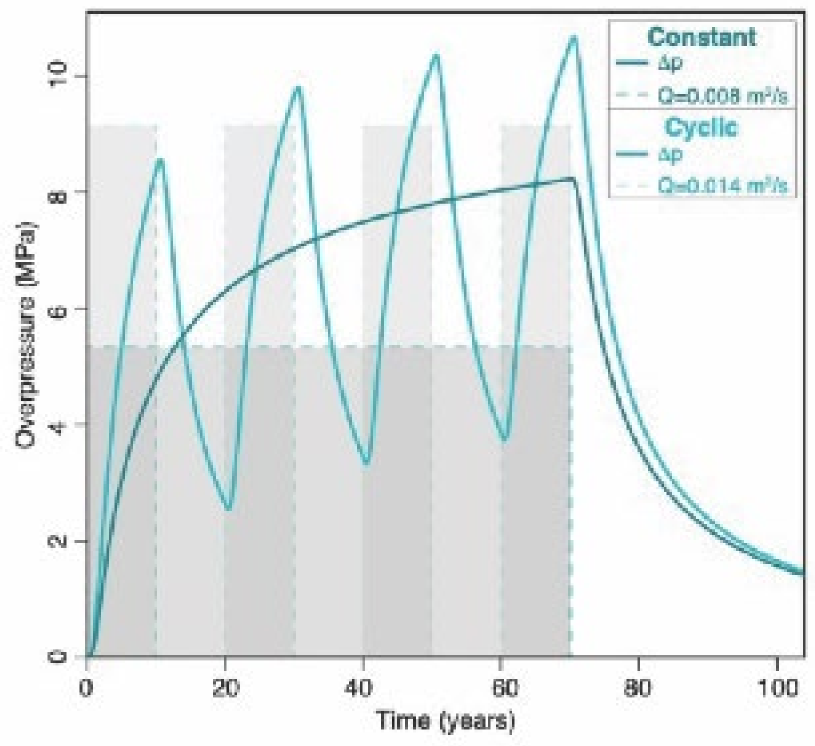

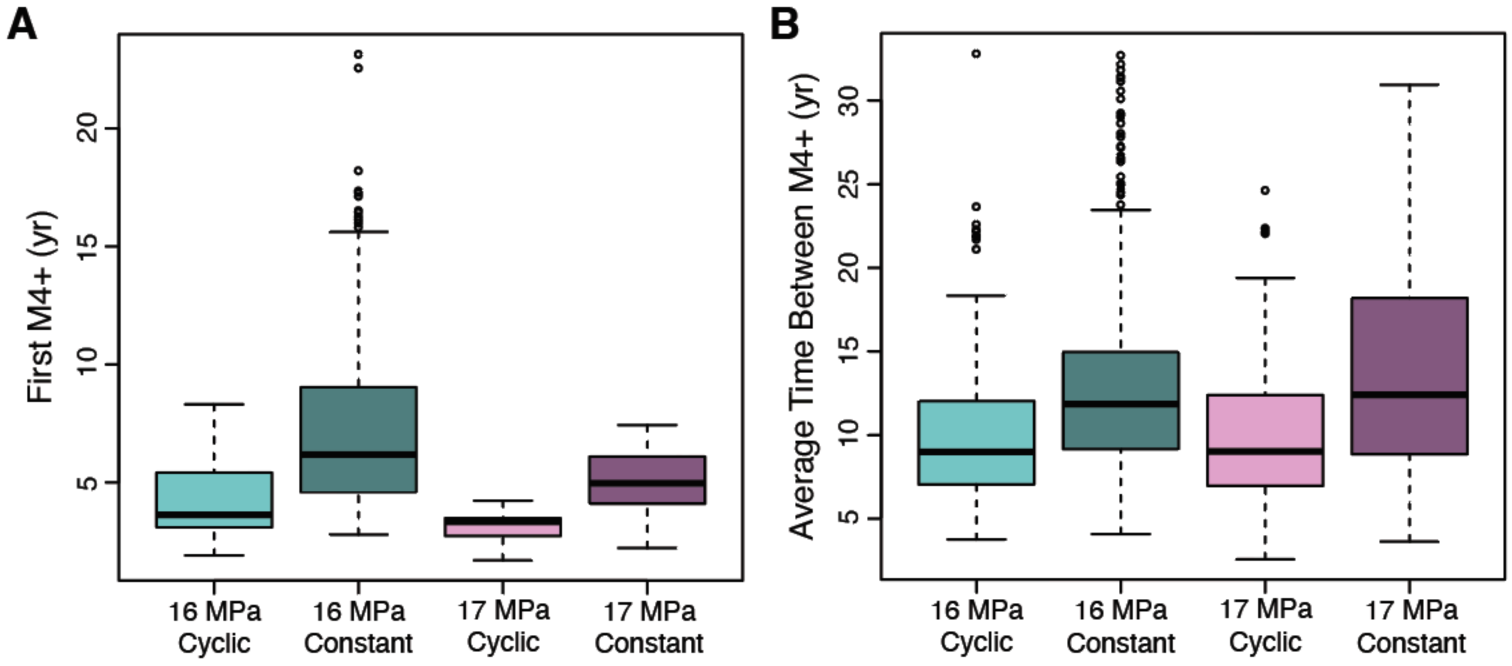

Kroll and Cochran, 2023

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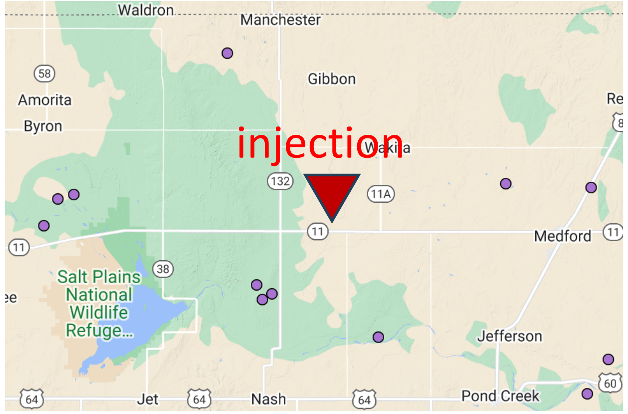
Pacific Northwest NATIONAL LABORATORY

Background seismicity module

- Provide seismic history given a proposed injection location
- Generate a catalog of seismicity given available continuous waveform data
- Improve pre-injection seismic risk assessment
- Facilitate Class VI permit application

Seismic history

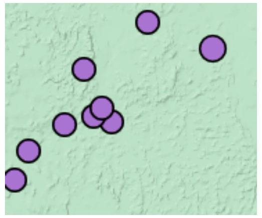


1.1	9 km ESE of Jefferson, Oklah... 2024-06-29 14:50:09 (UTC-06:...	7.7 km
1.3	8 km N of Nash, Oklahoma 2024-06-29 11:09:40 (UTC-06:...	7.0 km
1.5	8 km NNE of Nash, Oklahoma 2024-06-28 11:36:59 (UTC-06:...	6.5 km
1.5	9 km N of Nash, Oklahoma 2024-06-28 11:35:39 (UTC-06:...	8.8 km
1.1	7 km NW of Wakita, Oklahoma 2024-06-23 01:10:43 (UTC-06:...	5.8 km
1.0	7 km WNW of Wakita, Oklaho... 2024-06-20 23:13:34 (UTC-06:...	8.0 km

Waveform data

Module

Seismicity catalog

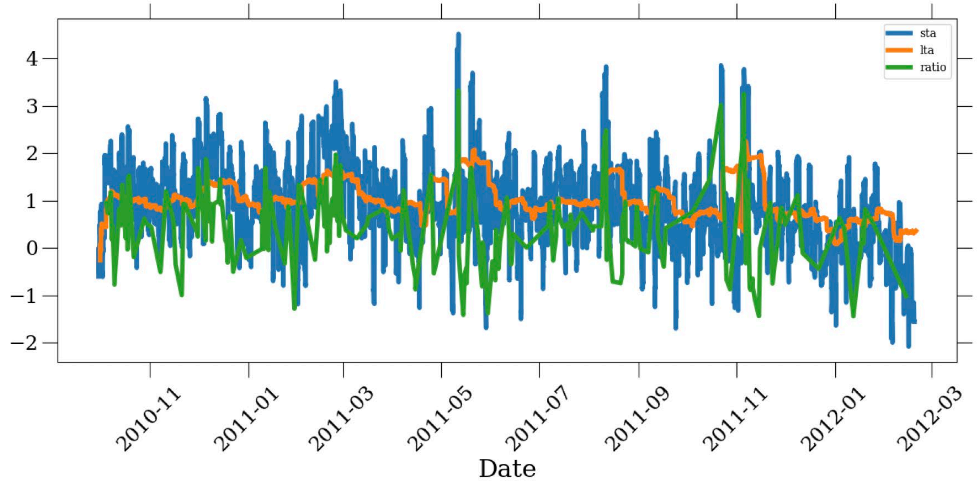


Seismic risk assessment

Monitor the fault state with seismicity

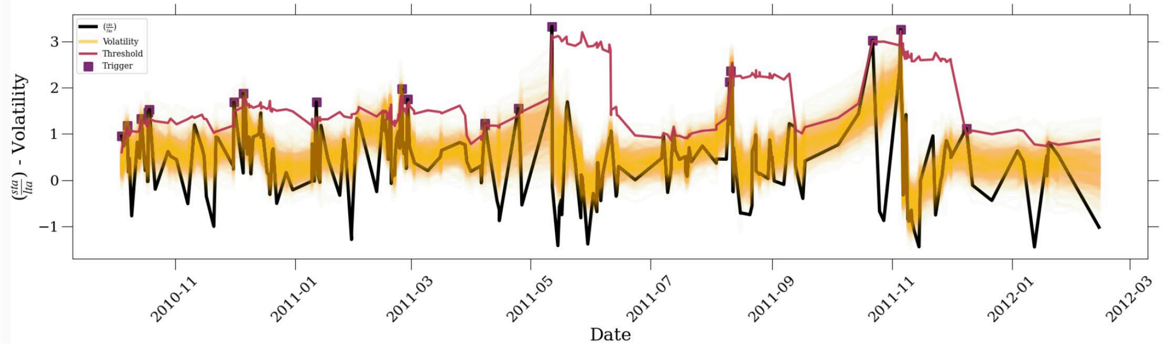
Modeling seismicity to understand the changing state of stress

Characterize temporal variation of seismicity

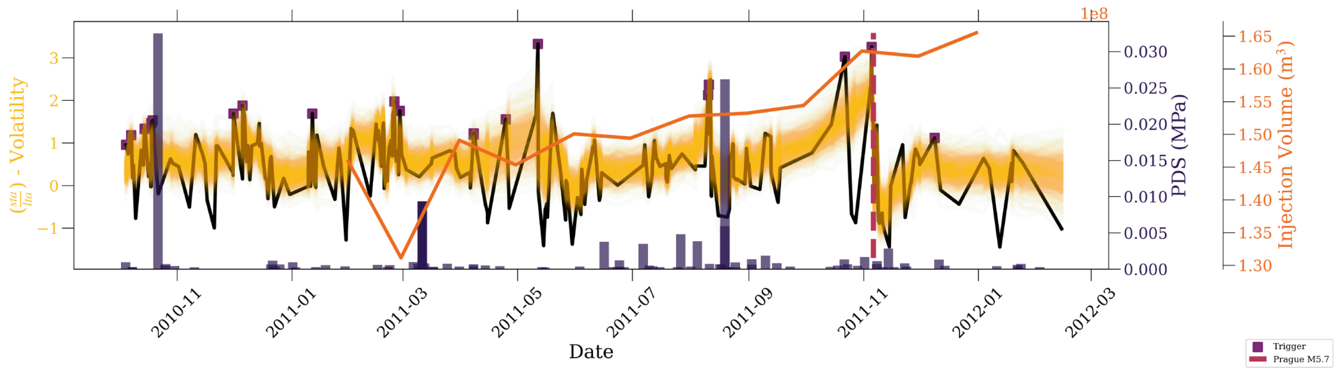


- Temporal pattern in seismicity contains useful information about the fault state
- We developed a Bayesian model to capture the evolution of seismicity and identify anomalies as indicators for changes in the state of stress

Probabilistic modeling of seismicity volatility

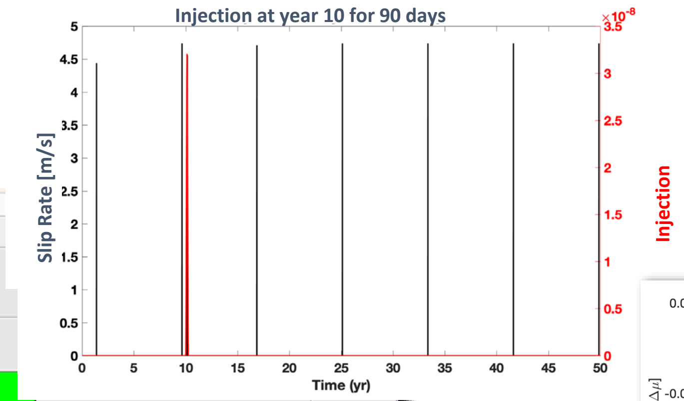


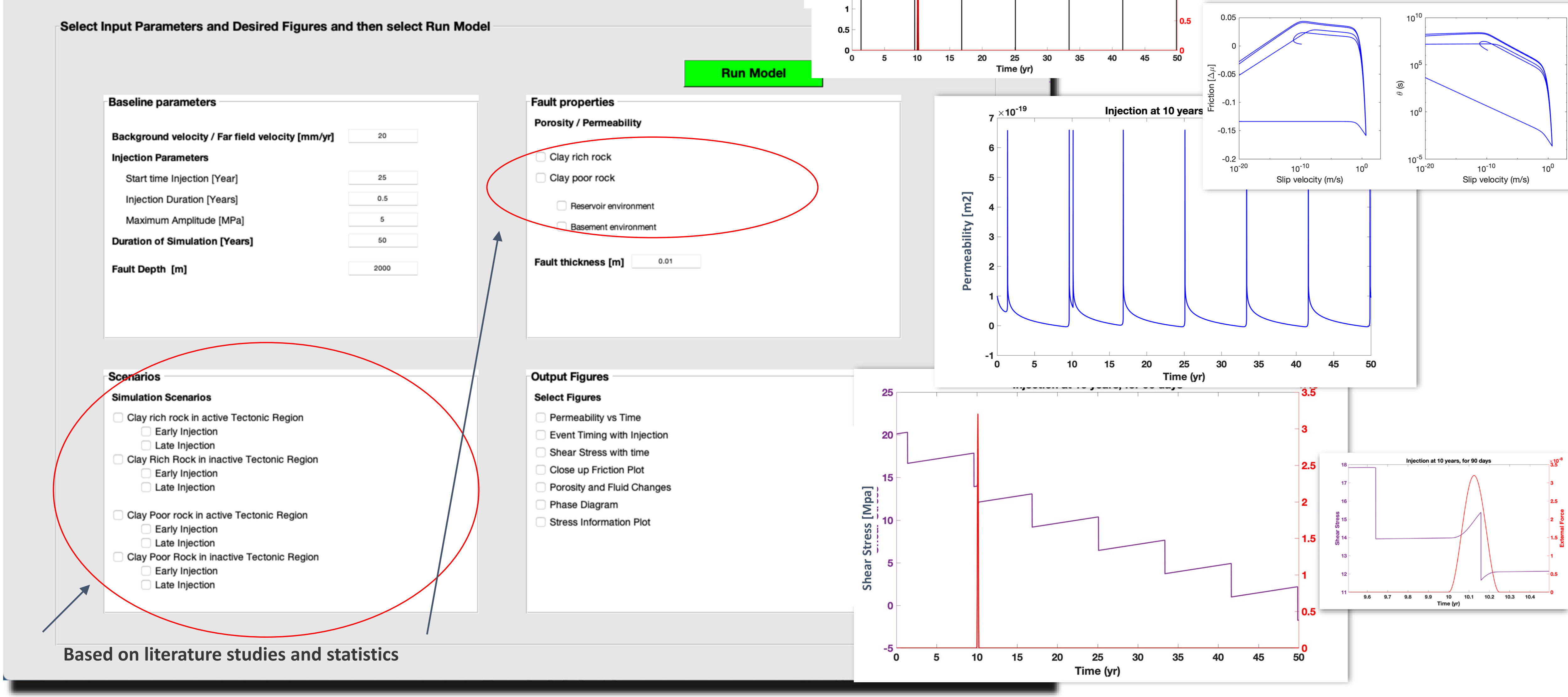
Identify changes in the state of stress



NRAP ROM Fault Seismic Stability with permeability changes

C.E. Layland-Bachmann, Y. Guglielmi and F. Cappa
LBNL, Berkeley

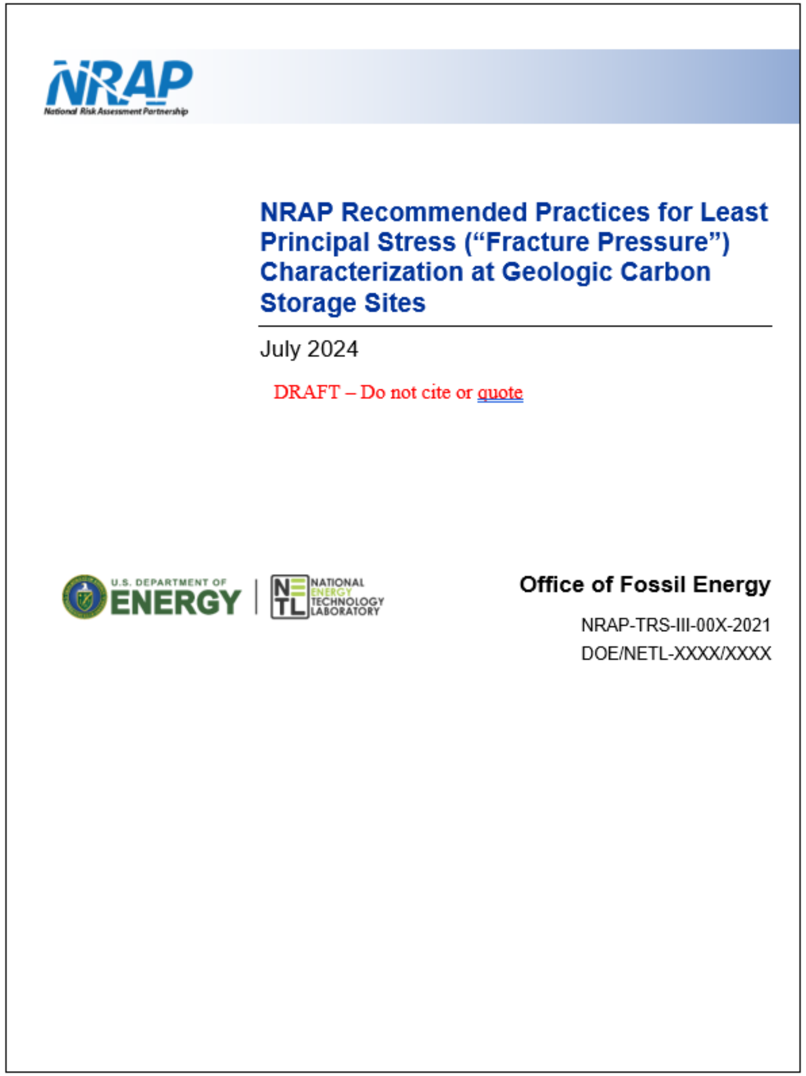




NRAP State-of-Stress Recommended Practices

- Current guides (ASTM D4645, ISRM): not GCS specific, dated/expired
- GCS industry unfamiliar with nuances of stress measurement

- RP focuses on methods to characterize the "fracture pressure"
- Received feedback from 17 experts from industry, academia, labs, and government
- Overwhelmingly positive feedback
- Expected release in Spring 2025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NRAP Recommended Practices for Least Principal Stress ("Fracture Pressure") Characterization at Geologic Carbon Storage Sites

July 2024

DRAFT – Do not cite or quote

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Fracture Pressure : An Ambiguous Term

1 **Fracture initiation pressure:** Pressure at which a fracture is formed, very difficult to predict with accuracy as it is governed by multiple factors such as defects of the rock, mud filter cake, etc.

2 **Breakdown Pressure:** Peak of the pressure vs. time curve; strongly influenced by wellbore storage effects, pumping rate, fluid type, and near-wellbore fracture geometry

3 **Fracture Propagation Pressure (FPP):**

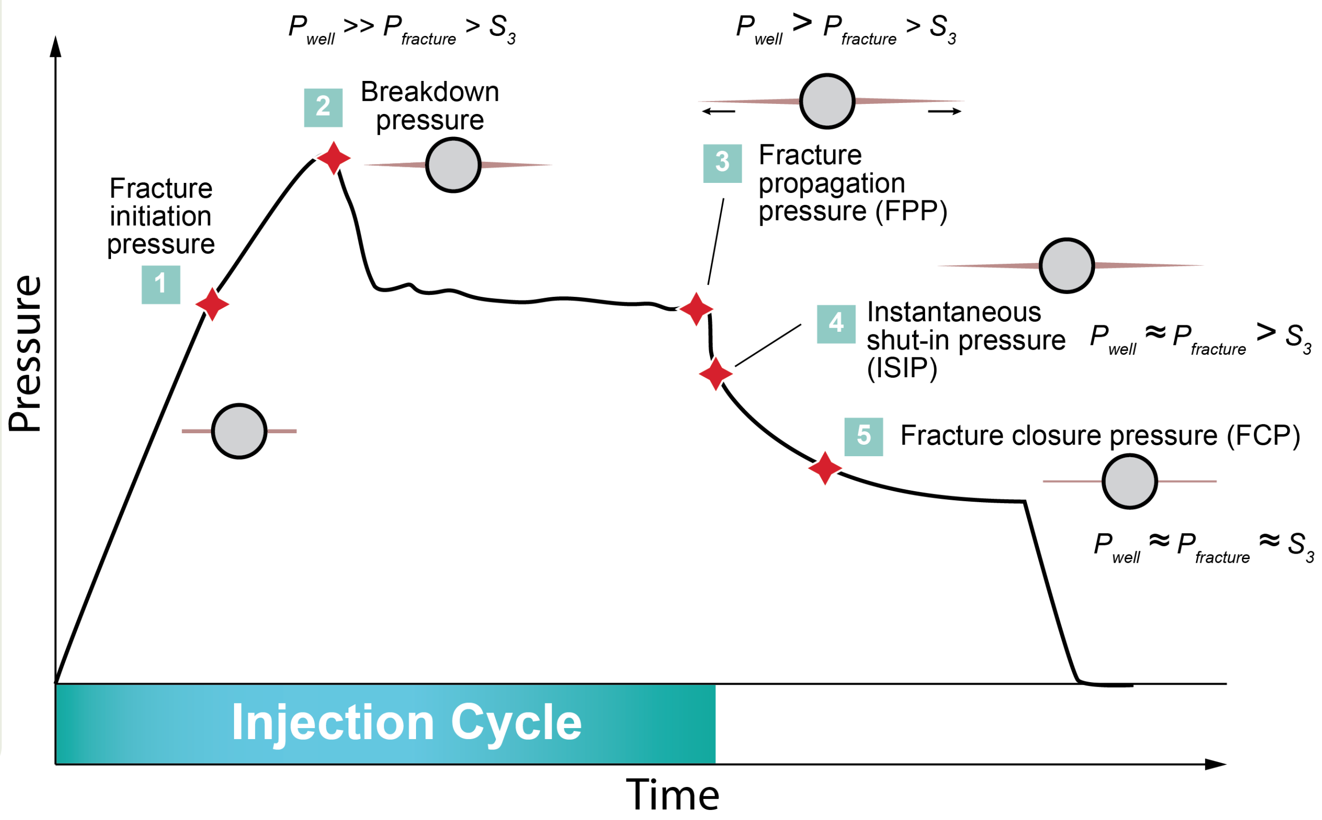
- FPP with water is usually 1-5 MPa above σ_3, depends on injection rate and perforation/open-hole and degree of fracture tortuosity
- FPP with CO_2 is likely to be less than 1 MPa above σ_3
- Some operators use FPP or even breakdown pressure, and may not conduct tests to determine FCP

4 **Instantaneous Shut-in Pressure (ISIP):**

- ISIP is equal to FPP but without viscous pressure loss
- ISIP is always greater than FCP and σ_3, and therefore not conservative

5 **Fracture Closure Pressure (FCP):**

- Best estimate of σ_3
- Can be determined through shut-in or controlled flowback test
- Fracture cannot propagate if injection pressure is below this value regardless of fluid or injection rate/duration
- Most conservative metric to use for injection pressure limit



Bayesian Uncertainty Quantification for Stresses

Joint prior distribution

$$\Pi_0(S_H, S_h)$$

Bayes' theorem

Joint posterior distribution from observations

$$\Pi\,(S_H, S_h \mid obs) = \frac{\Pi\,(obs \mid S_H, S_h)\,\Pi_0(S_H, S_h)}{\Pi\,(obs)}$$

$\Pi_0(S_H, S_h)$: prior probability
$\Pi\,(obs \mid S_H, S_h)$: conditional probability, likelihood
$\Pi\,(obs)$: normalization term
$\Pi\,(S_H, S_h \mid obs)$: posterior probability

Bayesian Uncertainty Quantification for Stresses

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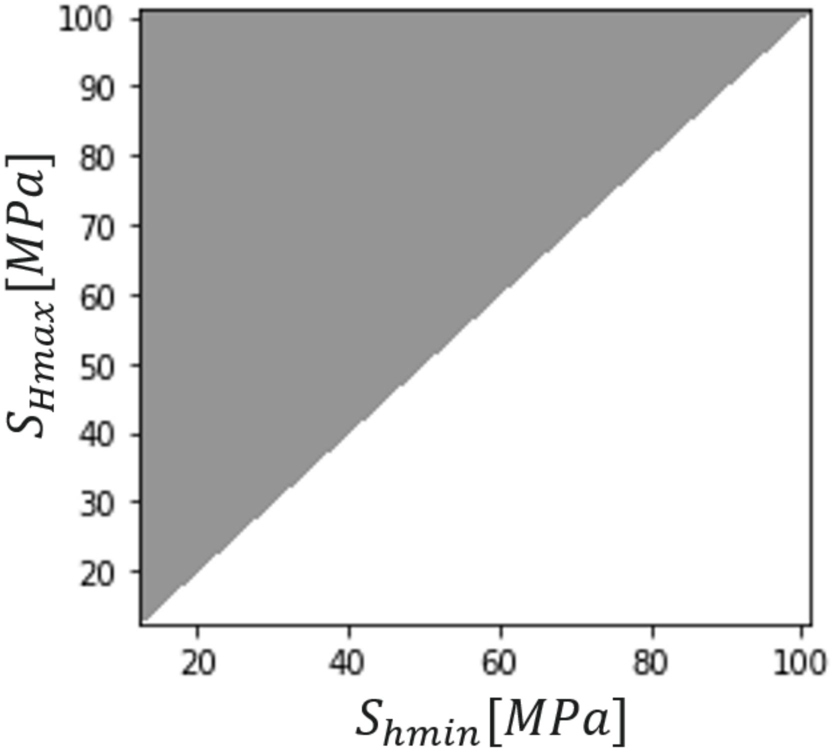
$$\Pi_0(S_H, S_h) = \begin{cases} 1, if\ S_{Hmax} \geq S_{hmin} > 0 \\ 0, otherwise \end{cases}$$



$\Pi\,(obs \mid S_H, S_h)$

Stress constraints (Burghardt 2018):

- Fault friction
- Regional Faulting regime
- Stress measurement
- Borehole breakout (BO)
- Drilling induced tensile fracture (DITF)

Bayesian Uncertainty Quantification for Stresses

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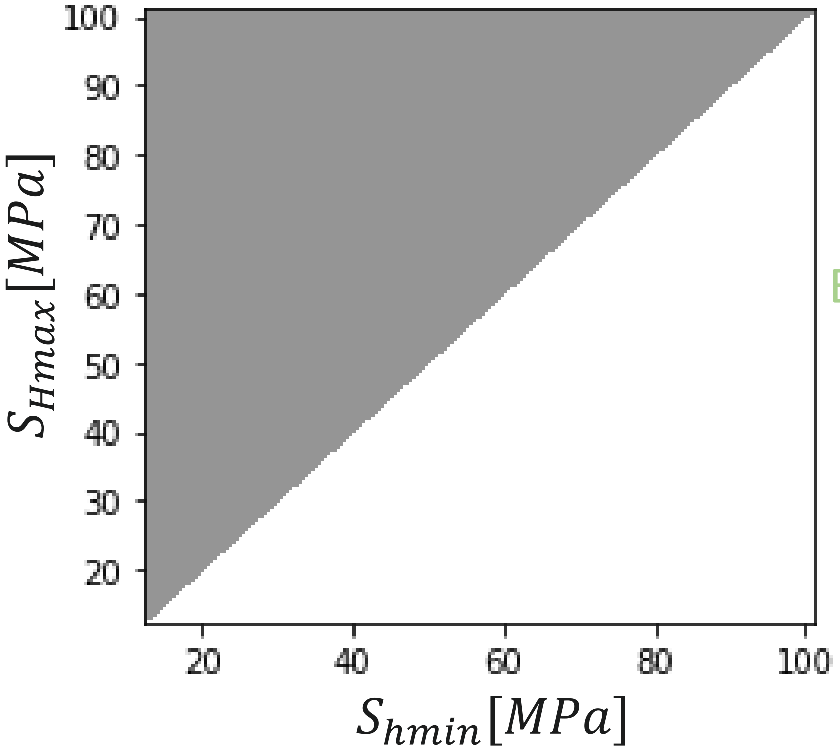
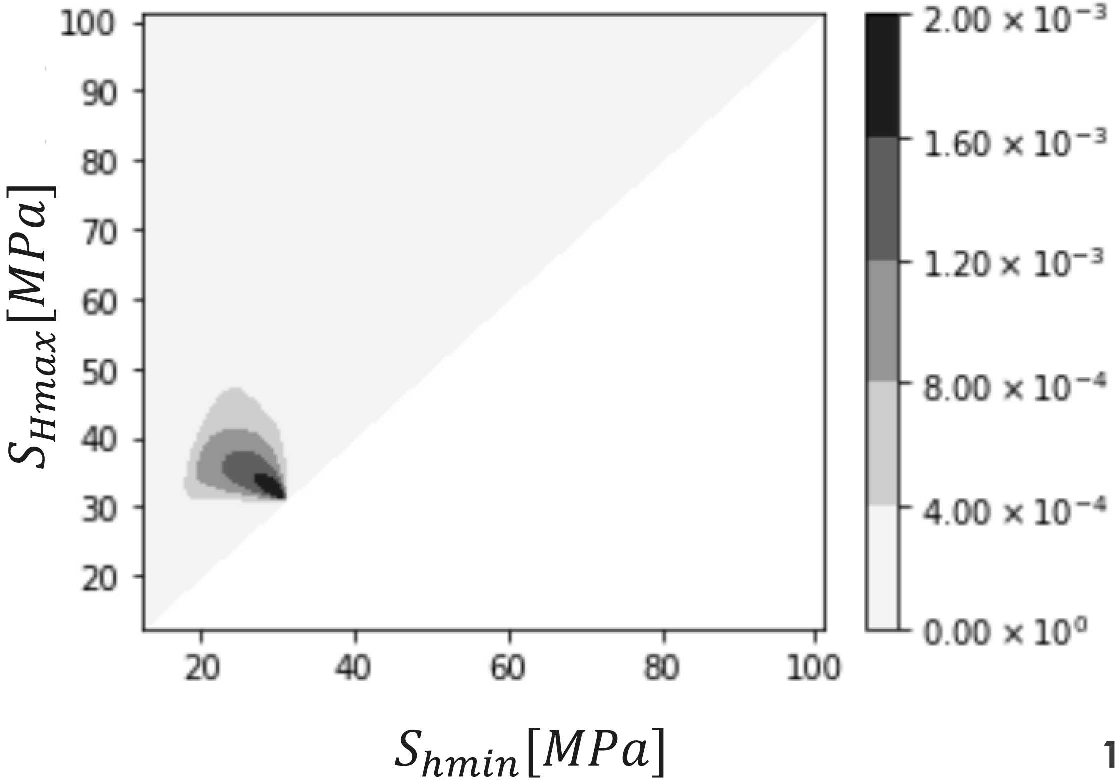
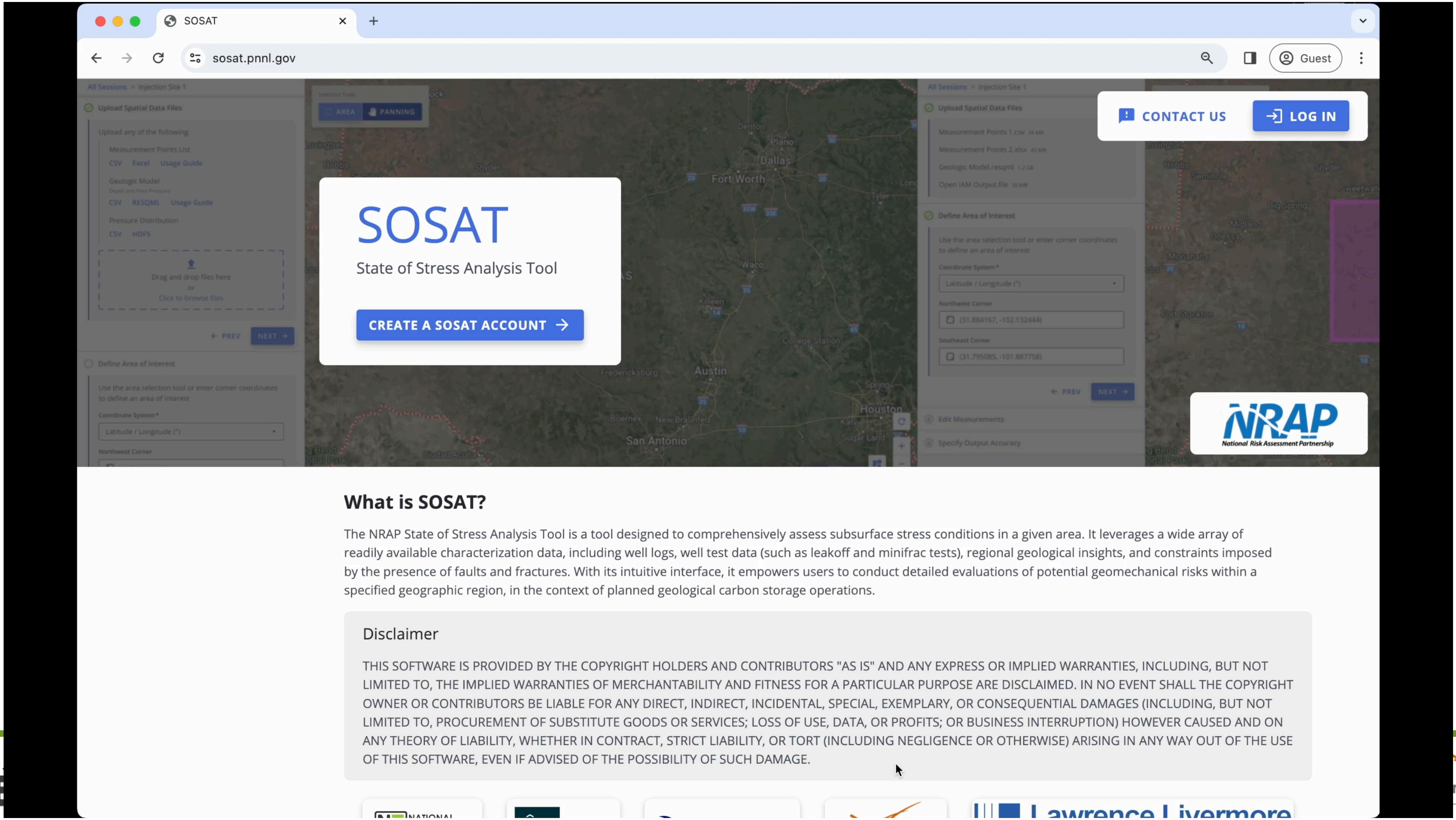


Bayes' theorem

- Fault friction
- Regional Faulting regime
- Stress measurement
- BO
- DITF



SOSAT demo


SOSAT
sosat.pnnl.gov
Guest
CONTACT US
LOG IN
SOSAT
State of Stress Analysis Tool
CREATE A SOSAT ACCOUNT →
NRAP
National Risk Assessment Partnership
What is SOSAT?
The NRAP State of Stress Analysis Tool is a tool designed to comprehensively assess subsurface stress conditions in a given area. It leverages a wide array of readily available characterization data, including well logs, well test data (such as leakoff and minifrac tests), regional geological insights, and constraints imposed by the presence of faults and fractures. With its intuitive interface, it empowers users to conduct detailed evaluations of potential geomechanical risks within a specified geographic region, in the context of planned geological carbon storage operations.
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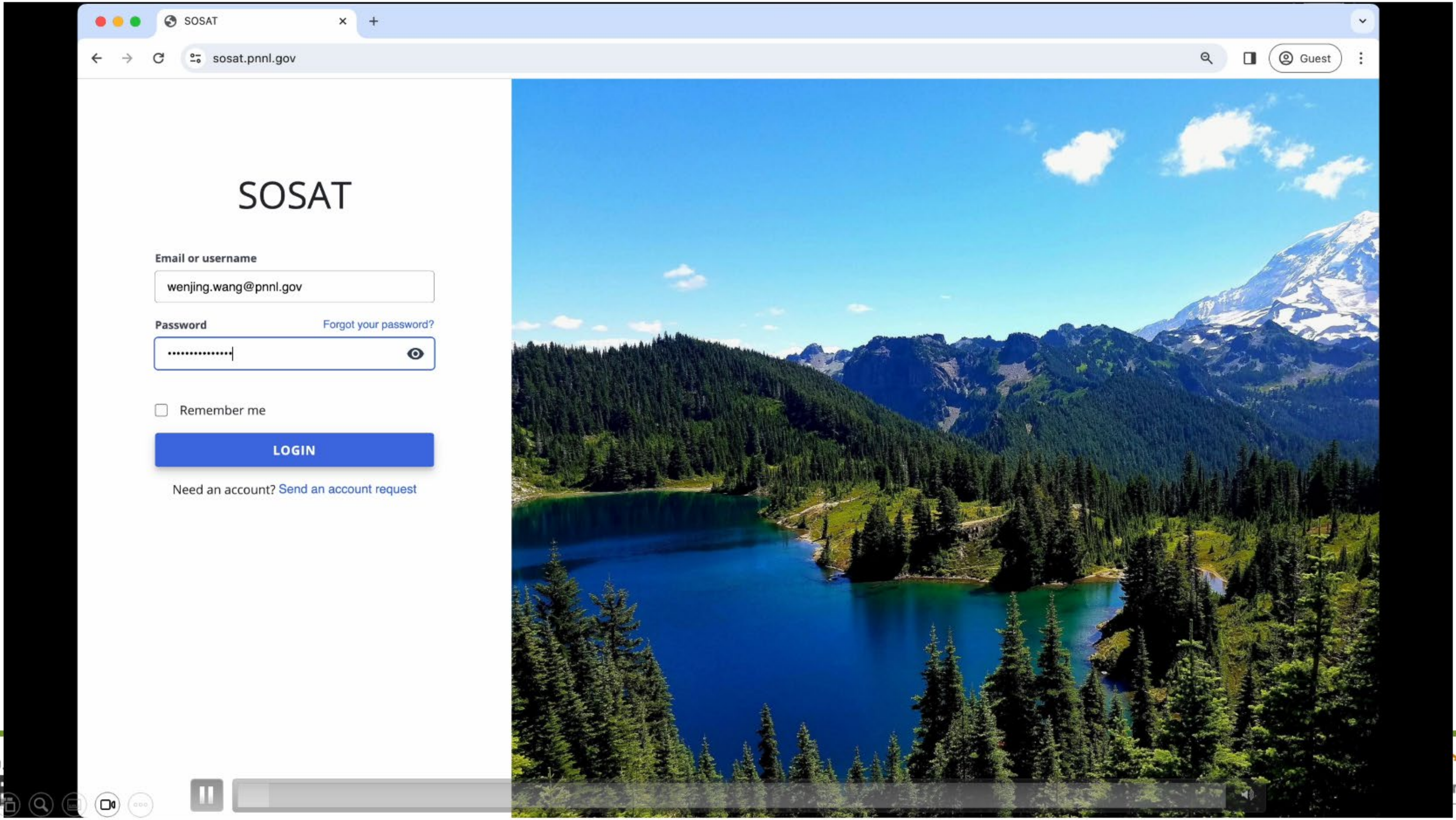
SOSAT demo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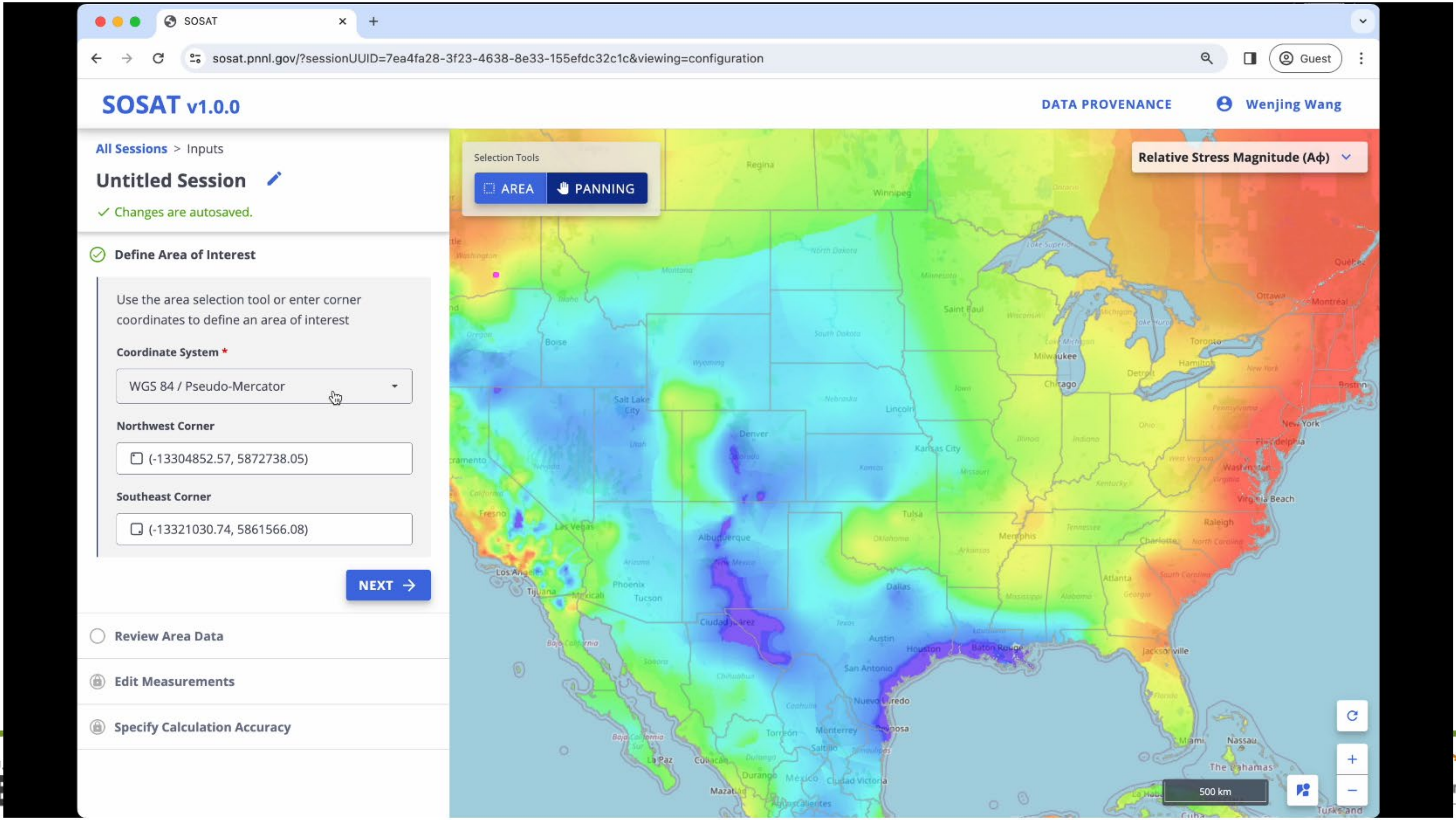
Password
Forgot your password?
Remember me
LOGIN
Need an account? Send an account request

SOSAT demo



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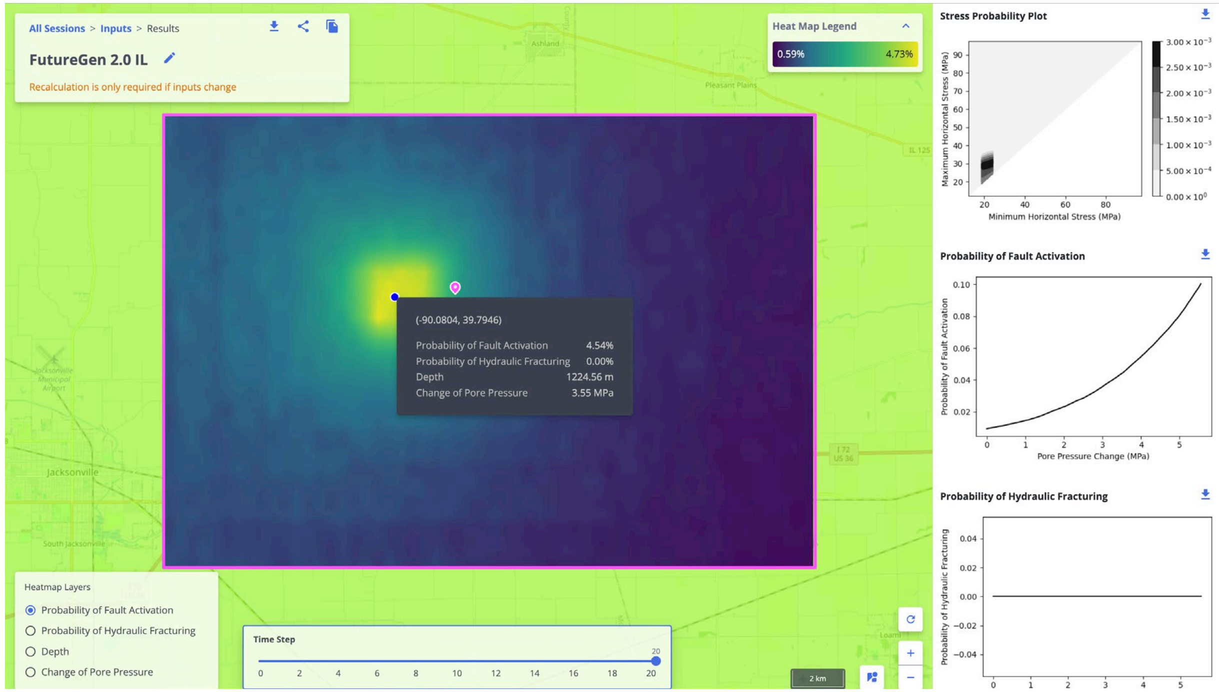
When Using SOSAT?

Applications involving subsurface fluid injection:

- Designing and screening subsurface fluid injection sites (analyze spatially)
- Managing risks throughout the operational periods (analyze temporally)
- Selecting appropriate injection pressures to manage geomechanical risks
- Guidance on whether additional field tests are needed to reduce stress uncertainty



Thank you!

Comments and Questions:

krollwhitesi1@llnl.gov

NRAP Website: https://edx.netl.doe.gov/nrap/

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Acknowledgement: This work was performed in support of the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management's Geo-Analysis and Monitoring Team and was developed jointly through the U.S. DOE Office of Fossil Energy and Carbon Management's EDX4CCS Project, in part, from the Bipartisan Infrastructure Law.