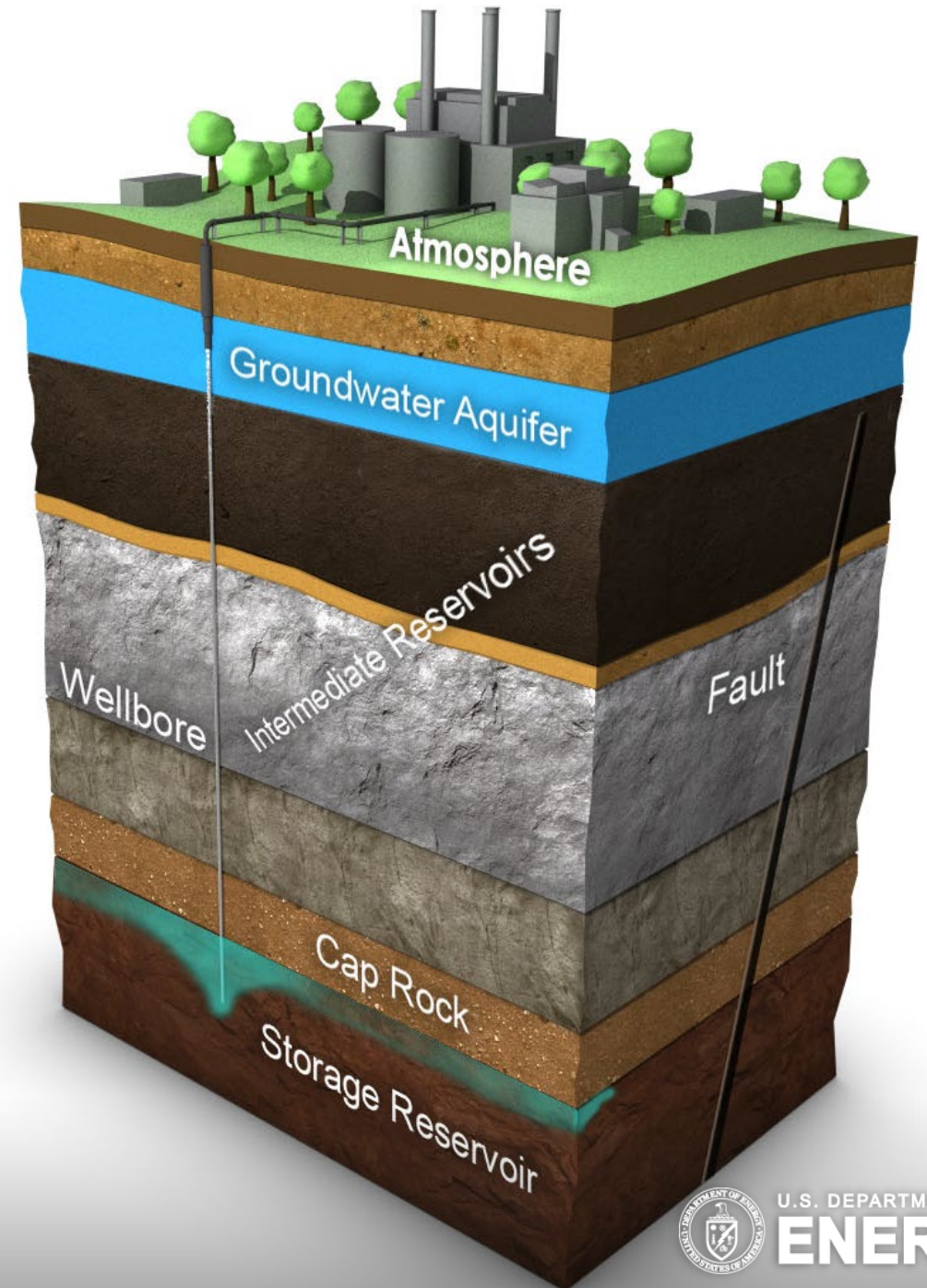


NRAP Task 3 - Induced Seismicity Risk Management

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



U.S. DEPARTMENT OF
ENERGY

Project Overview

Key Project participants

LLNL

- Kayla Kroll
- Chris Sherman
- Gina Geffers
- Chaoyi Wang

PNNL

- Jeff Burghardt
- Wenjing Wang
- Delphine Appriou

LBNL

- Yves Gugliemi
- Jonny Rutqvist
- Corinne Layland-Bachmann

LANL

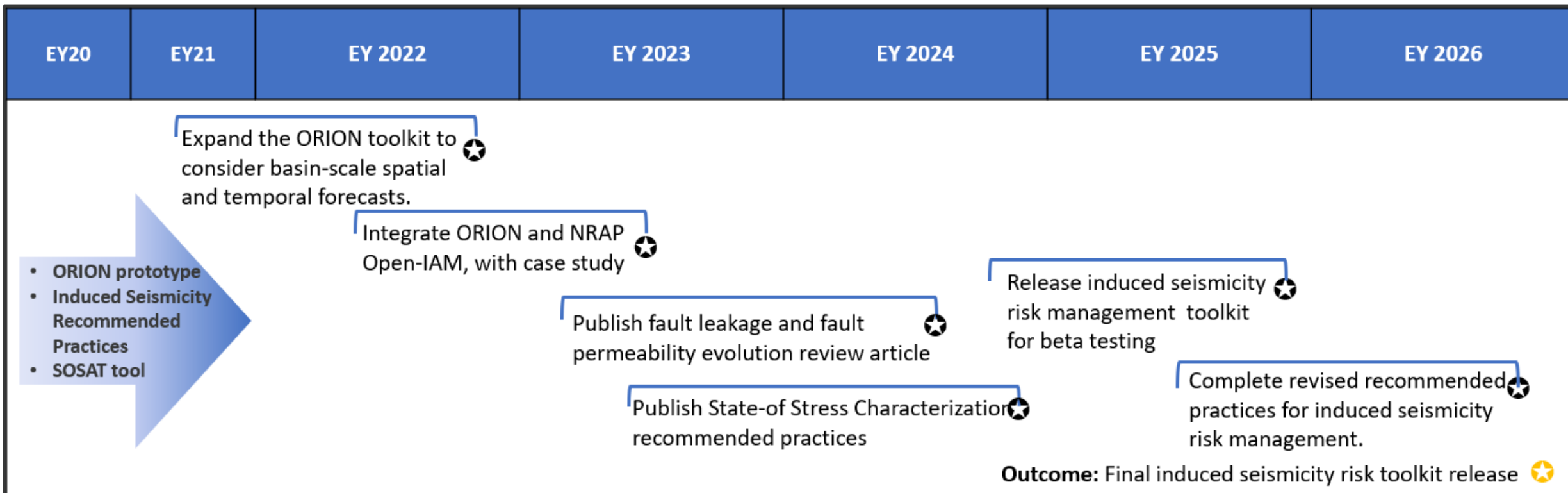
- Ting Chen

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.

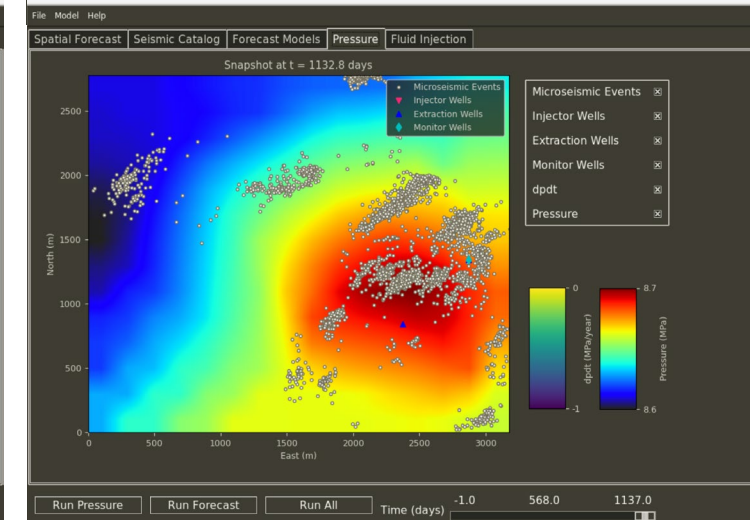
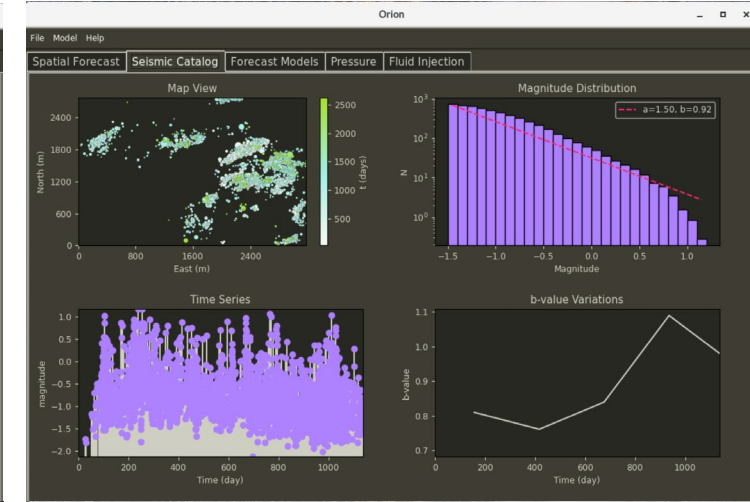
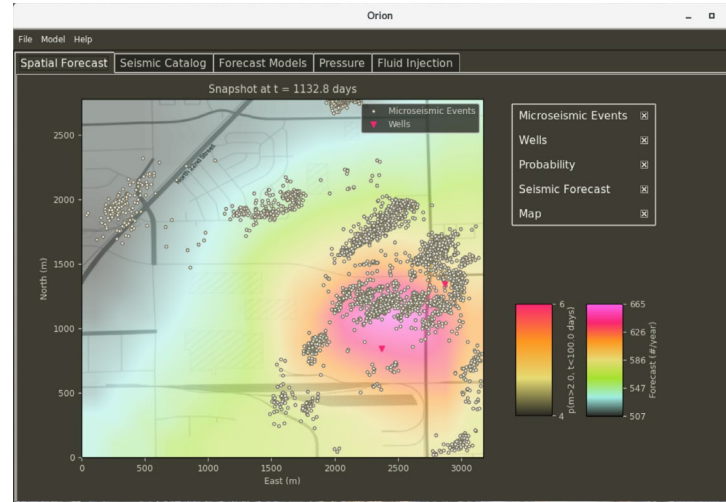




Basin Scale Spatio-temporal Forecasts

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)

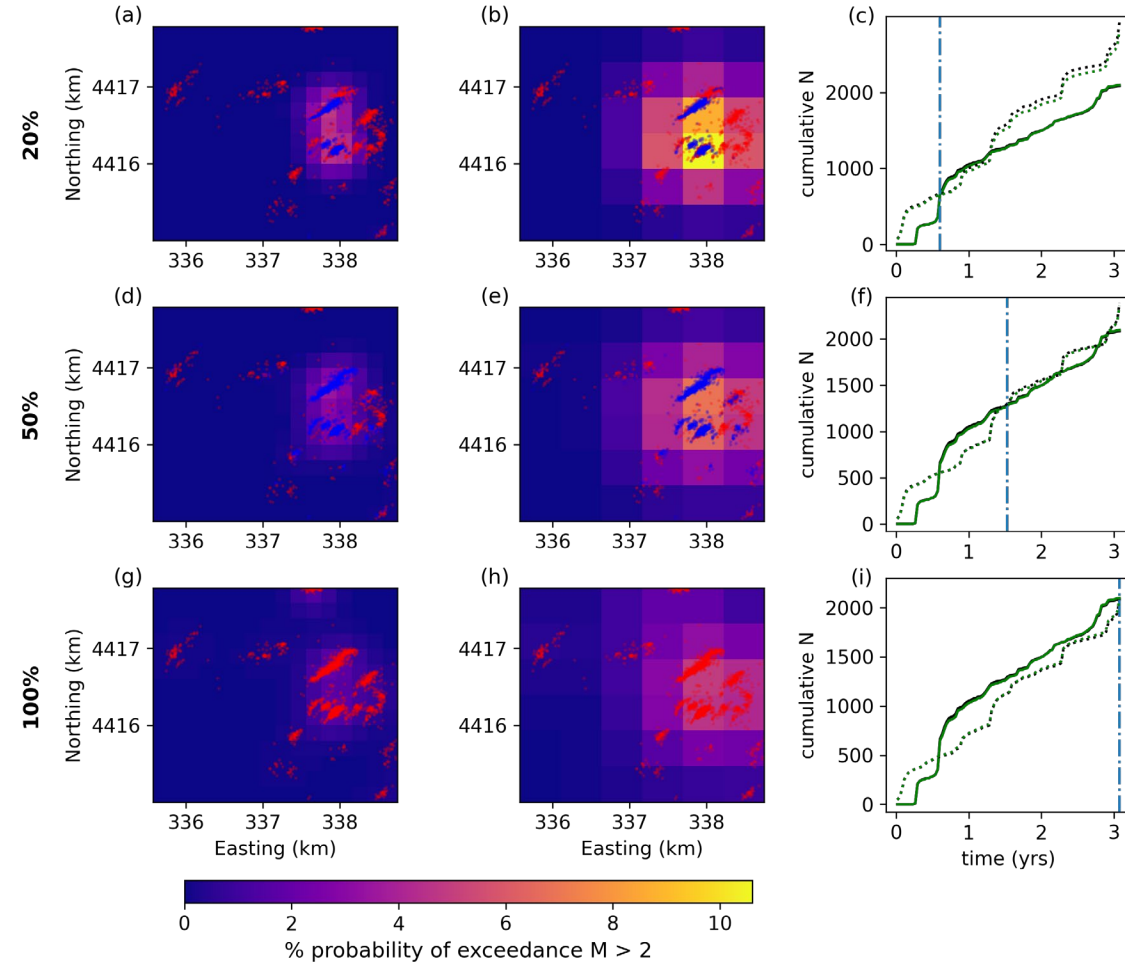
$$\dot{S} = \dot{\tau} - \mu(\dot{\sigma} - \dot{p})$$

\dot{p} = pressurization rate during injection

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

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

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

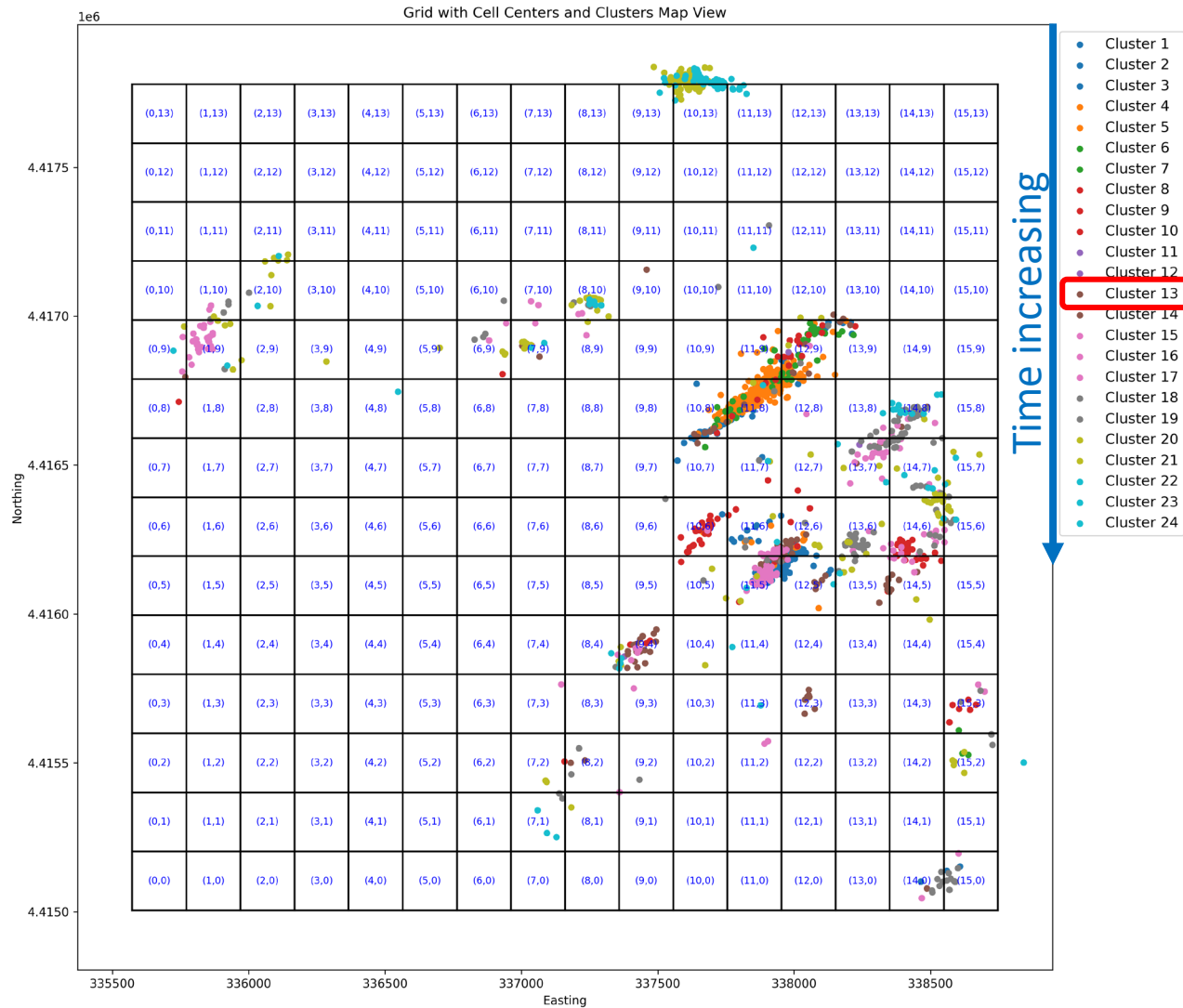


Submitted manuscript, April 2024:

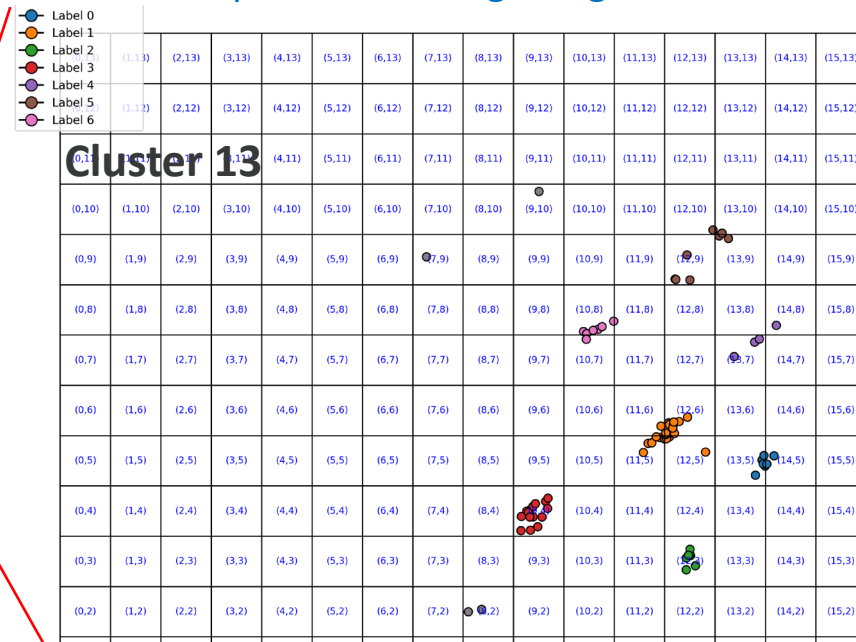
Geffers, G-M., K. A. Kroll, C. S. Sheman, C. Wang. Towards operational forecasting using the seismogenic index model for CO2 storage, SRL

Spatial-temporal clustering at IBDP site

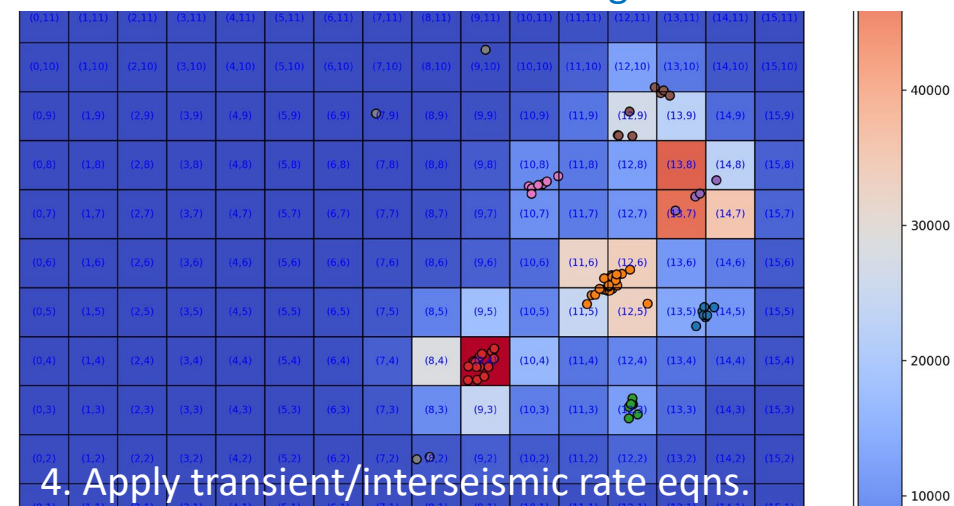
1. Auto temporal clustering using rate density



2. Auto spatial clustering using HDBSCAN



3. Calculate Coulomb stress change

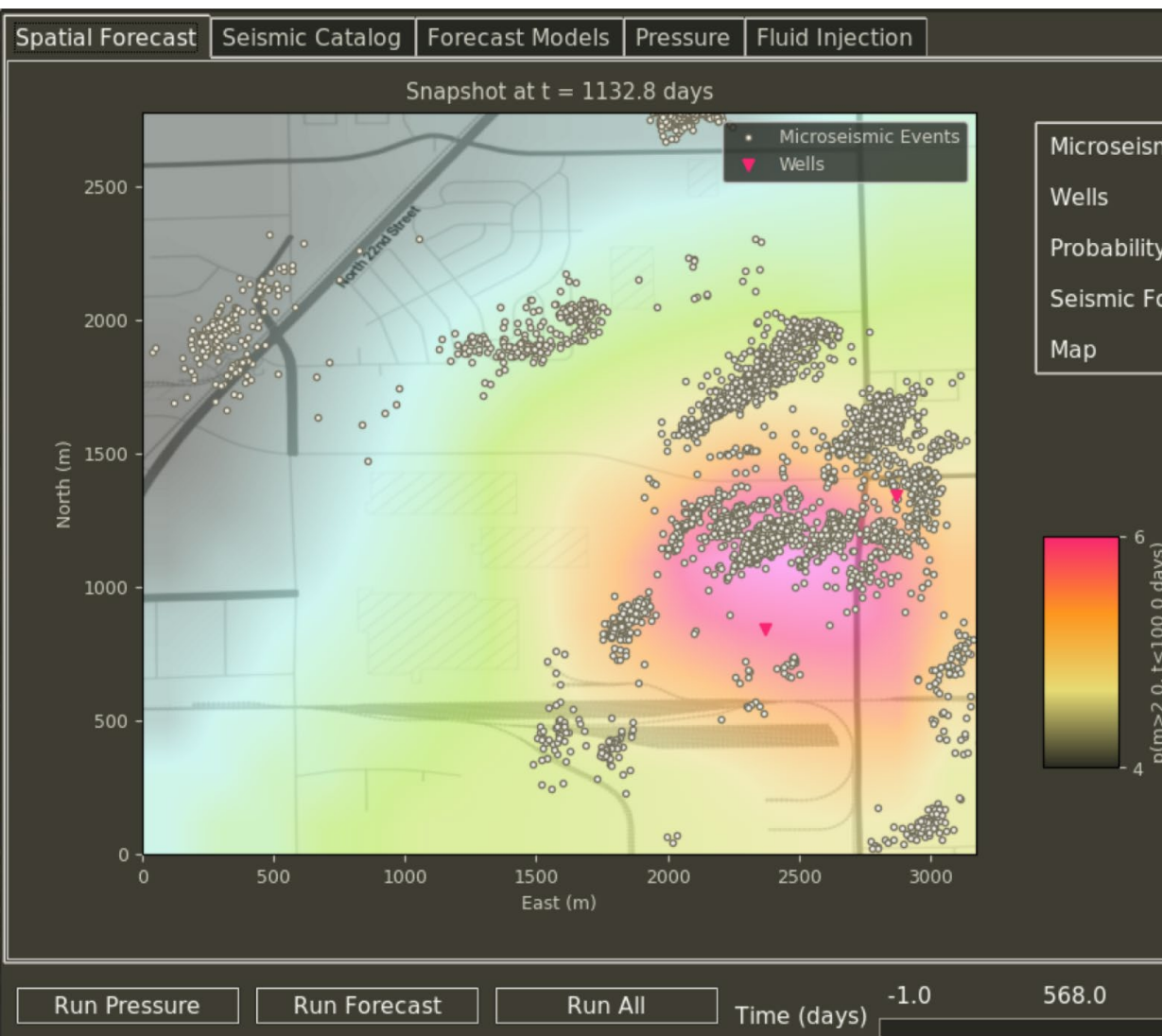


4. Apply transient/interseismic rate eqns.

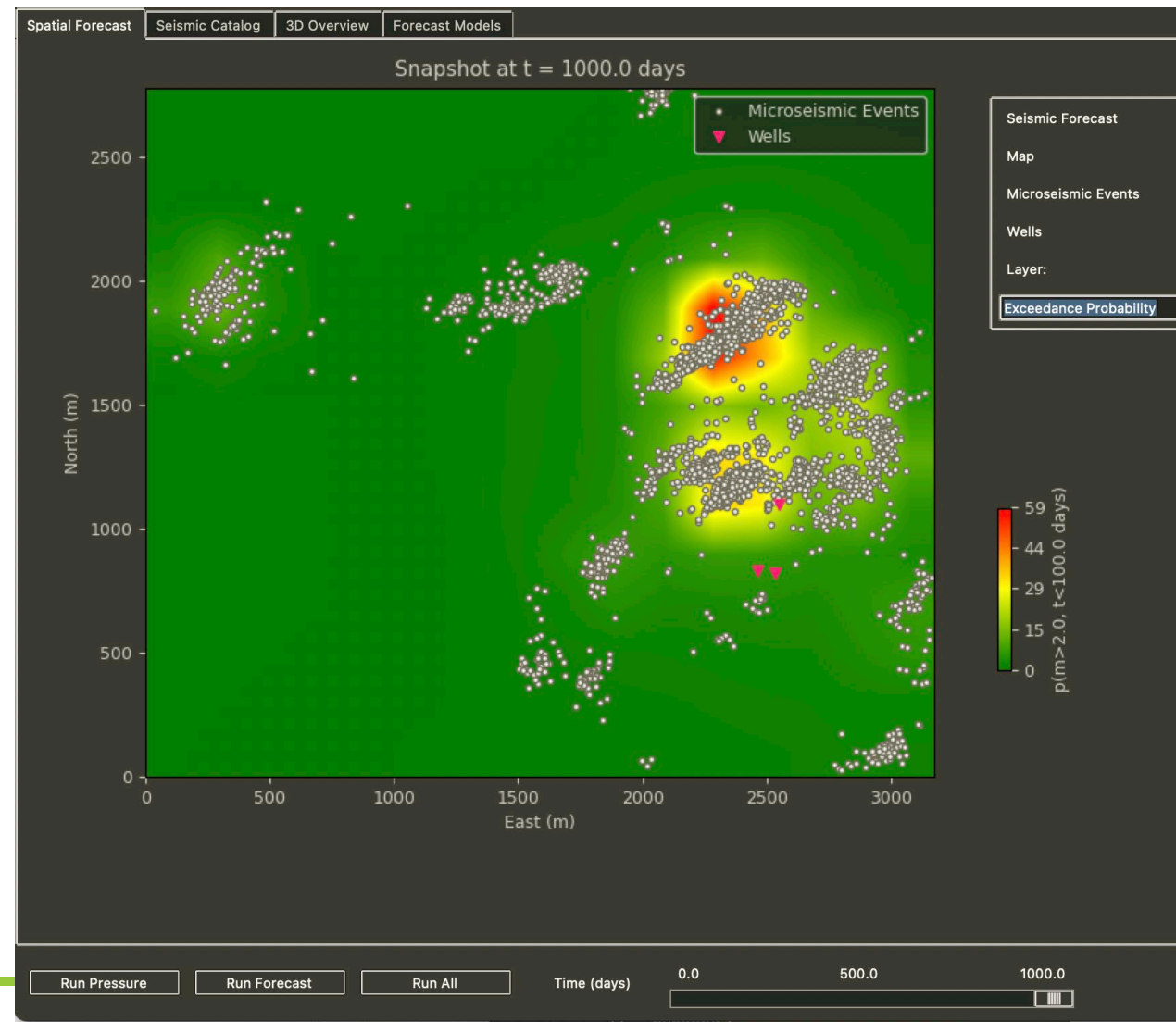
CRS model in action: Forecast using ORION for IBDP



Forecast **without** secondary triggering



Forecast **with** secondary triggering

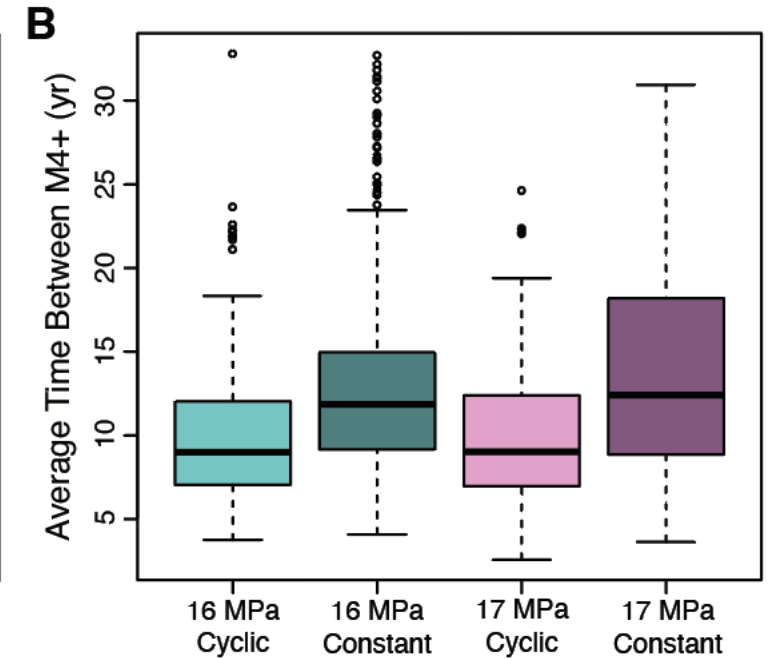
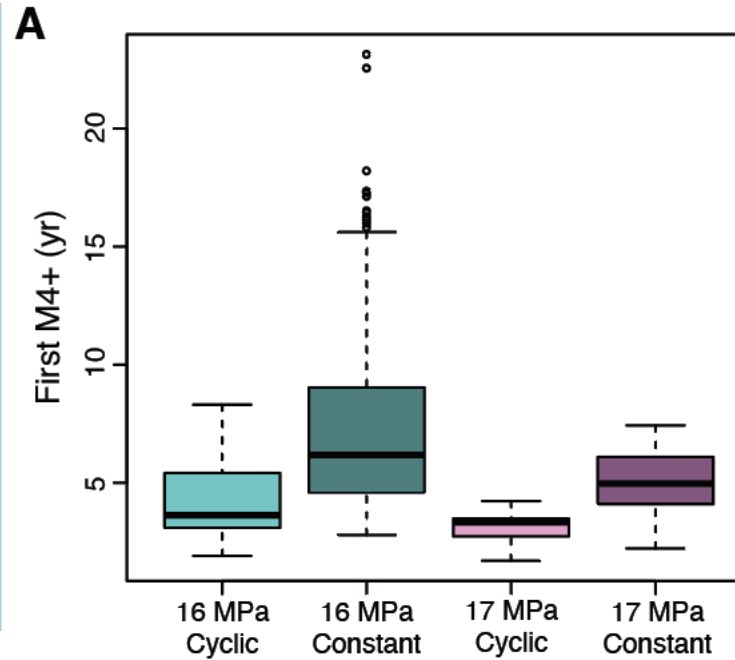
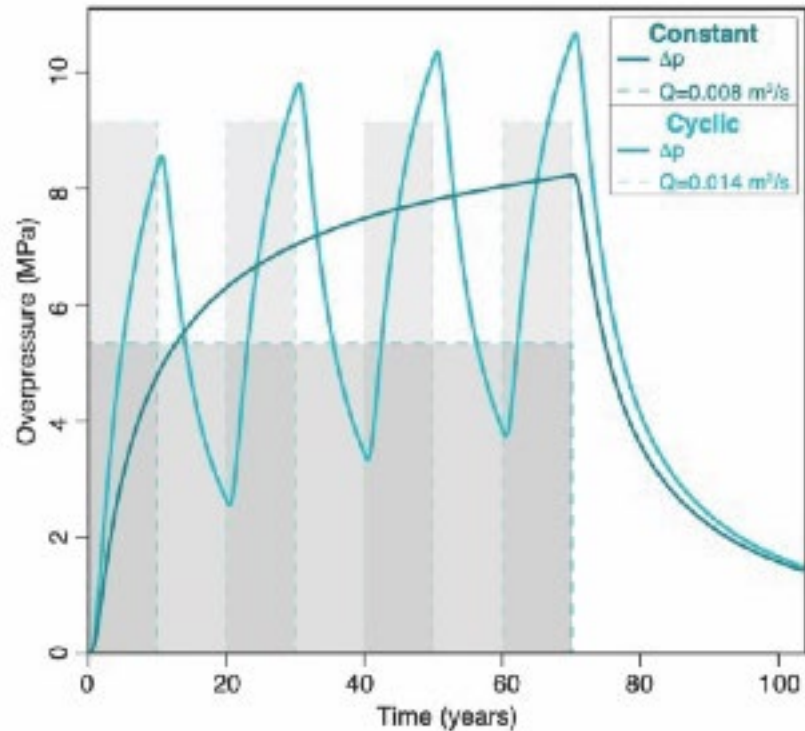


Basin Scale Spatio-temporal Forecasts

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. Kroll¹, Elizabeth S. Cochran² and Christopher S. Sherman¹
 kroll5@llnl.gov; ecochran@usgs.gov; sherman27@llnl.gov

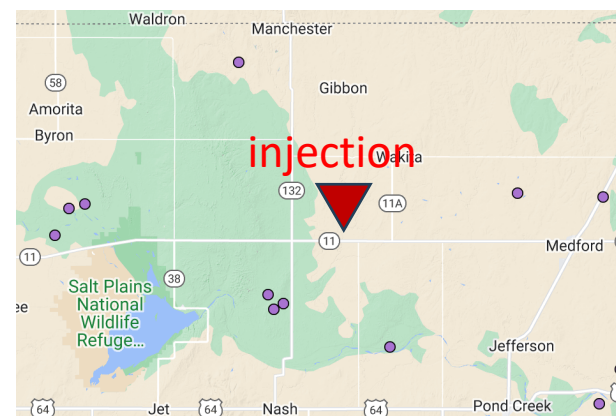


Kroll and Cochran, 2023 9

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

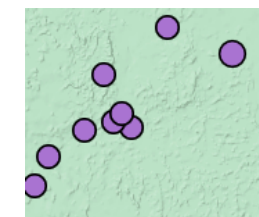
Waveform data



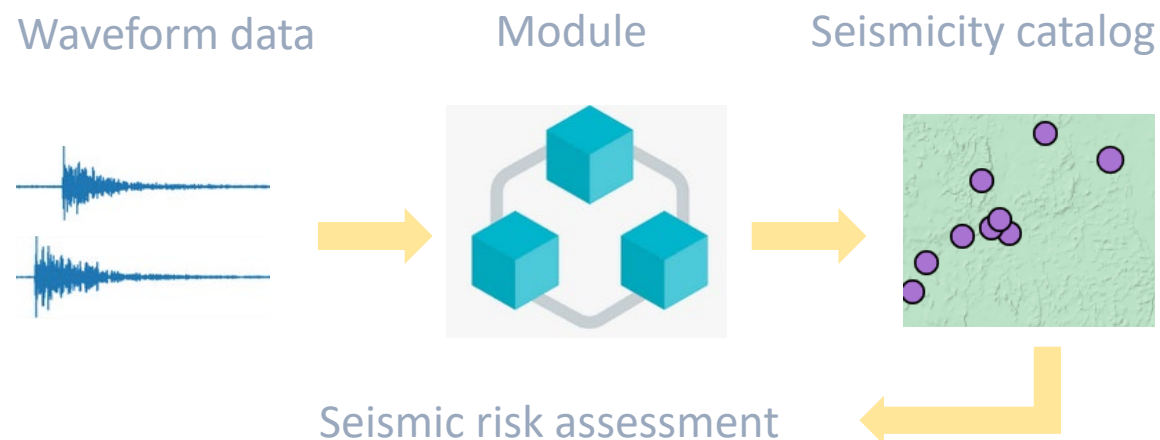
Module



Seismicity catalog



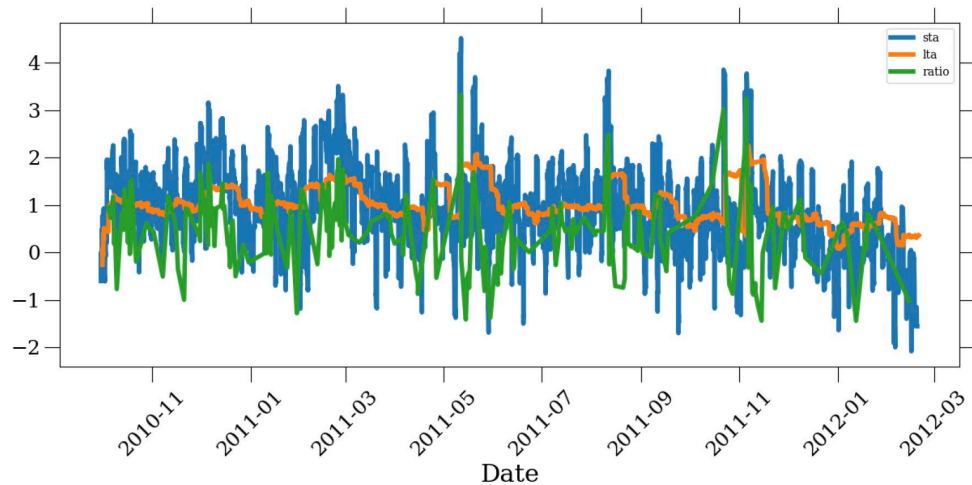
Seismic risk assessment



Monitor the fault state with seismicity

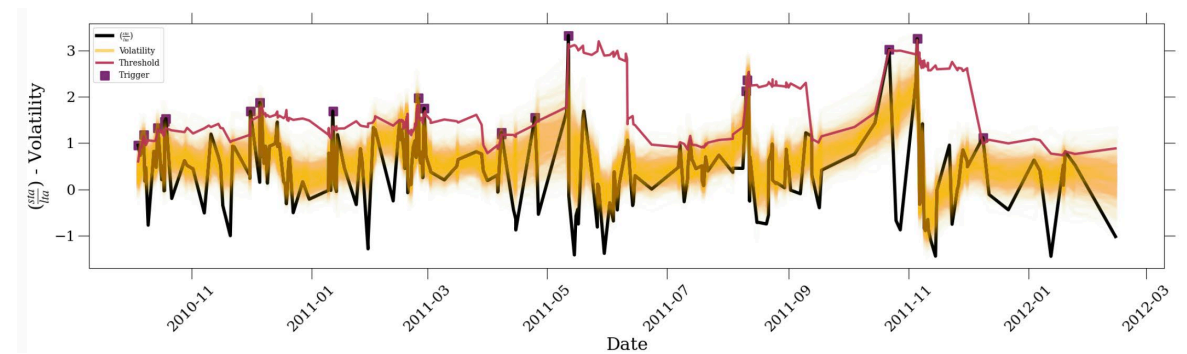
Modeling seismicity to understand the changing state of stress

Characterize temporal variation of seismicity

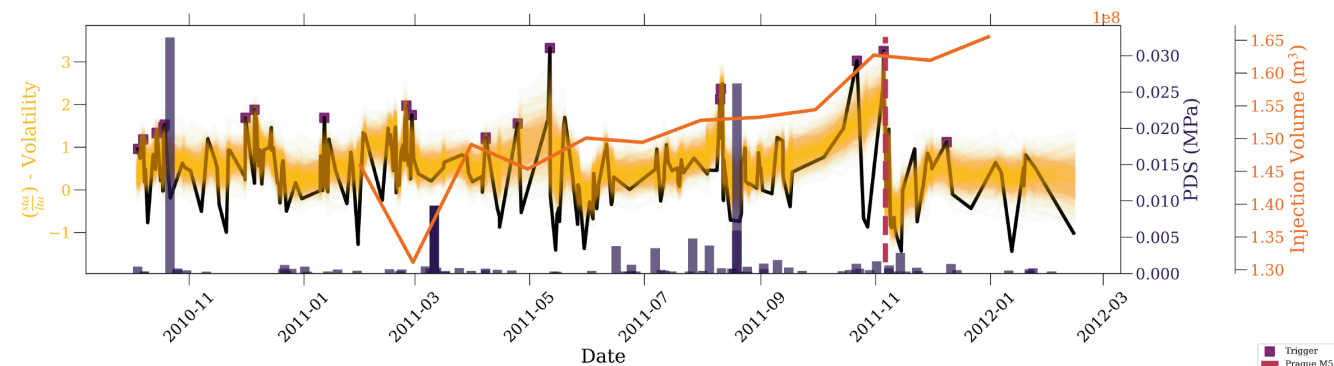


- Temporal pattern in seismicity contains useful information about the fault state
- We developed a Bayesian model to capture the evolution of seismicity and identify anomalies as indicators for changes in the state of stress

Probabilistic modeling of seismicity volatility



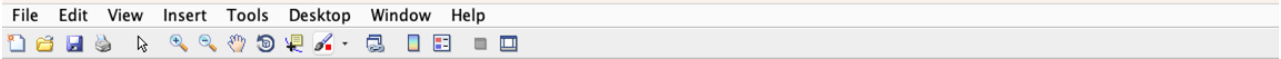
Identify changes in the state of stress



NRAP ROM Fault Seismic Stability with permeability changes

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

LBNL, Berkeley



Select Input Parameters and Desired Figures and then select Run Model

Run Model

Baseline parameters

Background velocity / Far field velocity [mm/yr]

Injection Parameters

Start time Injection [Year]

Injection Duration [Years]

Maximum Amplitude [MPa]

Duration of Simulation [Years]

Fault Depth [m]

Fault properties

Porosity / Permeability

Clay rich rock

Clay poor rock

Reservoir environment

Basement environment

Fault thickness [m]

Scenarios

Simulation Scenarios

Clay rich rock in active Tectonic Region

Early Injection

Late Injection

Clay Rich Rock in inactive Tectonic Region

Early Injection

Late Injection

Clay Poor rock in active Tectonic Region

Early Injection

Late Injection

Clay Poor Rock in inactive Tectonic Region

Early Injection

Late Injection

Output Figures

Select Figures

Permeability vs Time

Event Timing with Injection

Shear Stress with time

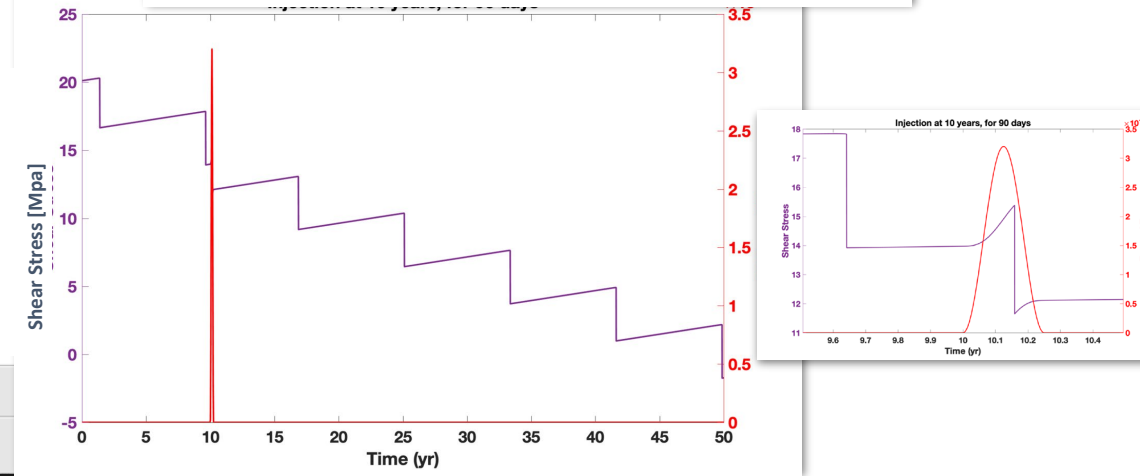
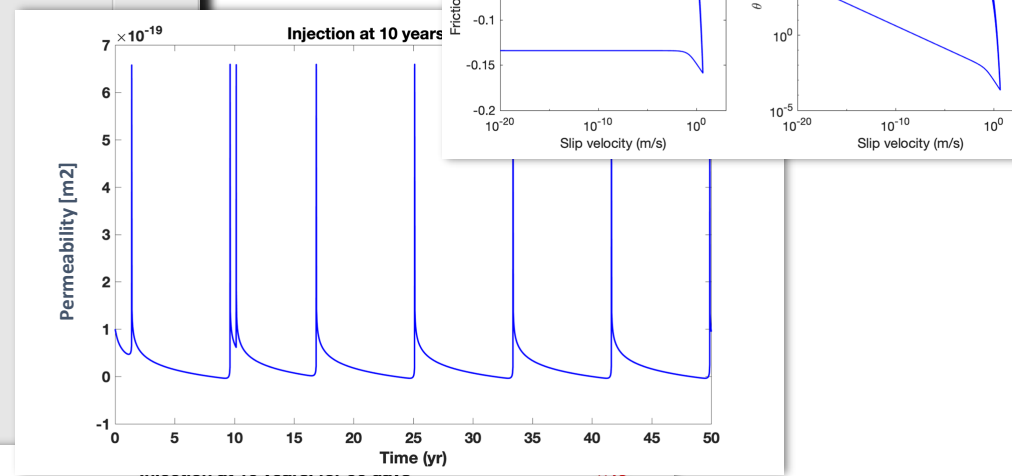
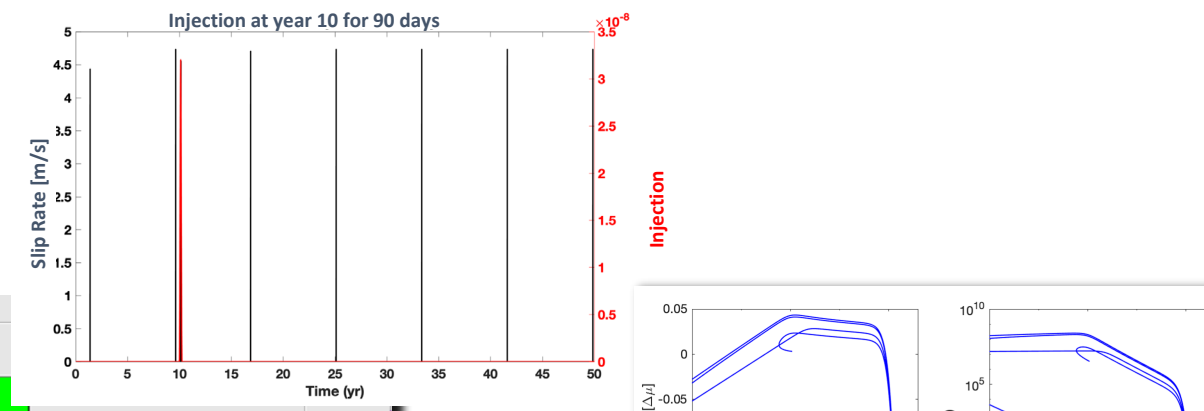
Close up Friction Plot

Porosity and Fluid Changes

Phase Diagram

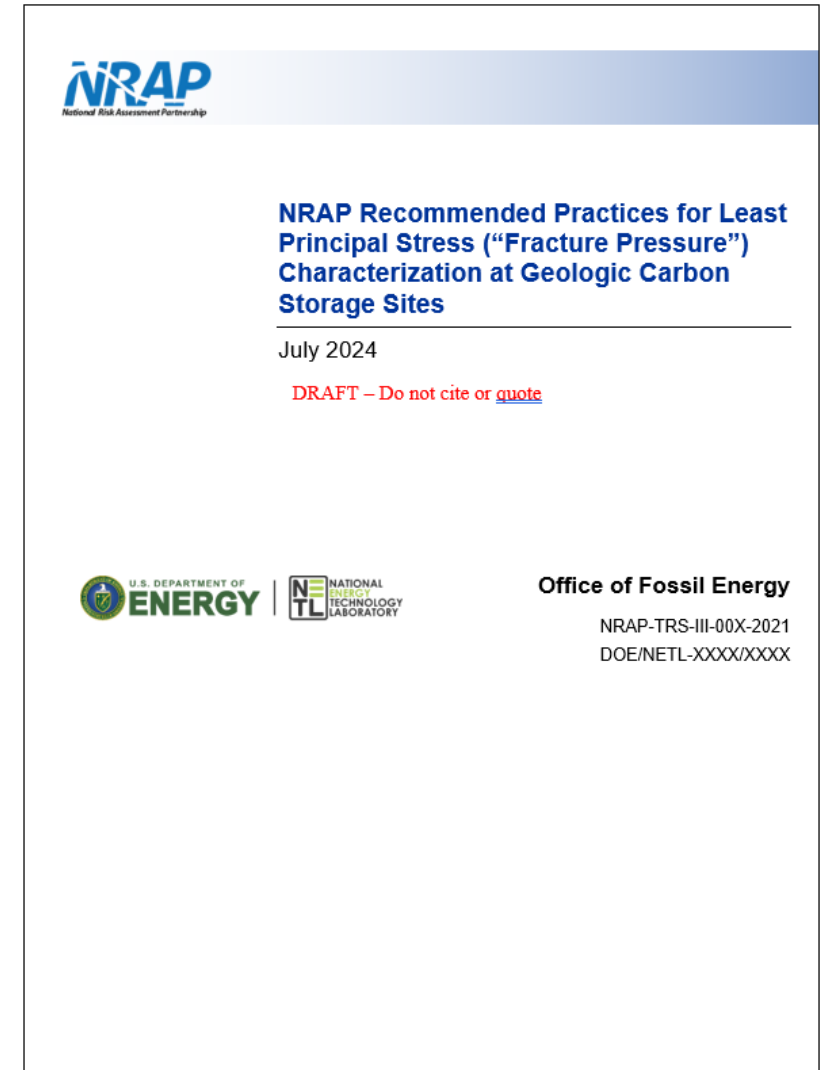
Stress Information Plot

Based on literature studies and statistics



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



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

Fracture Propagation Pressure (FPP):

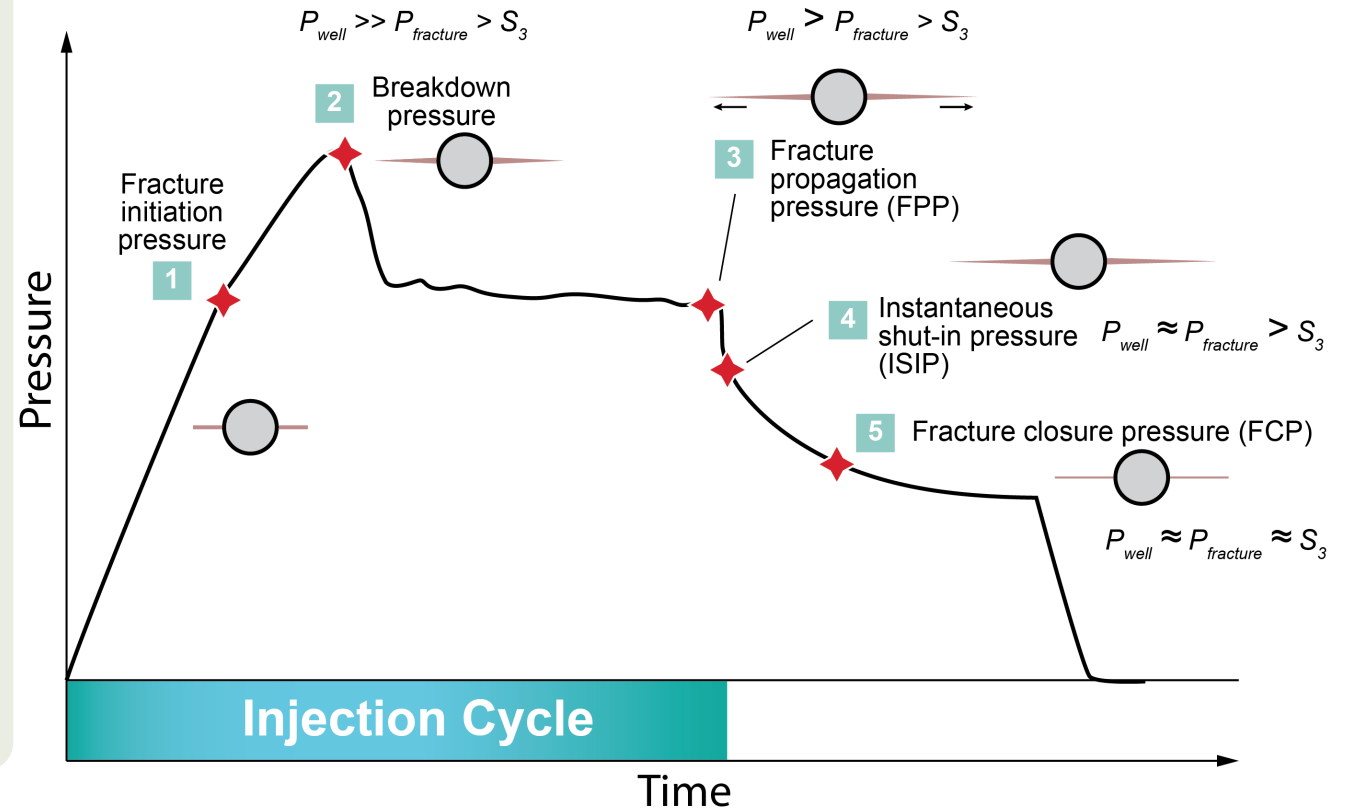
- FPP with water is usually 1-5 MPa above σ_3 , depends on injection rate and perforation/open-hole and degree of fracture tortuosity
- FPP with CO₂ is likely to be less than 1 MPa above σ_3
- Some operators use FPP or even breakdown pressure, and may not conduct tests to determine FCP

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

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

$\Pi_0(S_H, S_h)$: prior probability

$\Pi(obs | S_H, S_h)$: conditional probability, likelihood

$\Pi(obs)$: normalization term

$\Pi(S_H, S_h | obs)$: posterior probability

Bayesian Uncertainty Quantification for Stresses

Joint prior distribution

$$\Pi_0(S_H, S_h)$$

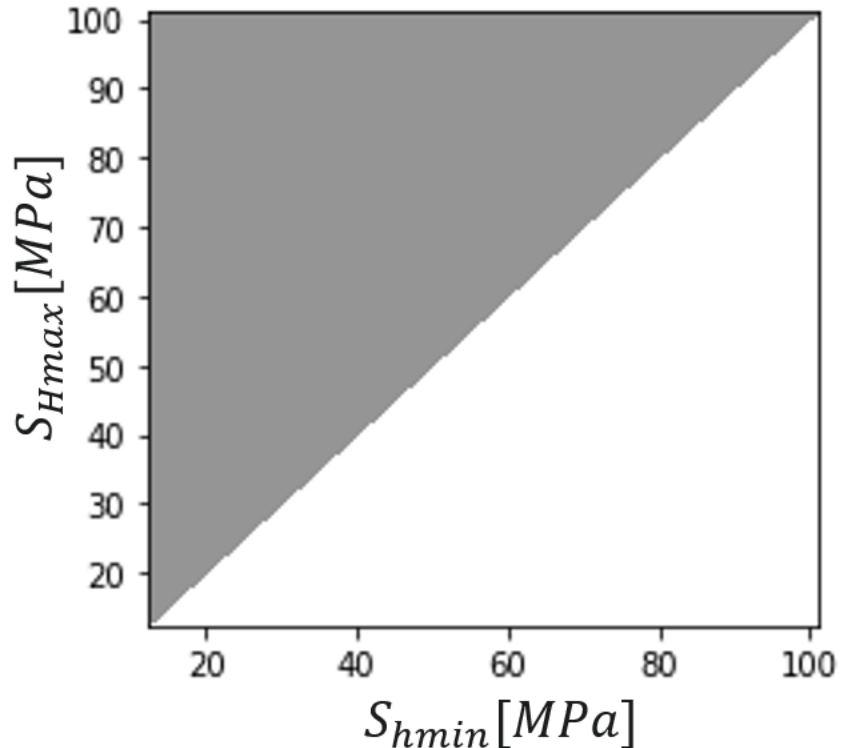
Bayes' theorem



Joint posterior distribution from observations

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

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



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

Stress constraints (Burghardt 2018):

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

Bayesian Uncertainty Quantification for Stresses

Joint prior distribution

$$\Pi_0(S_H, S_h)$$

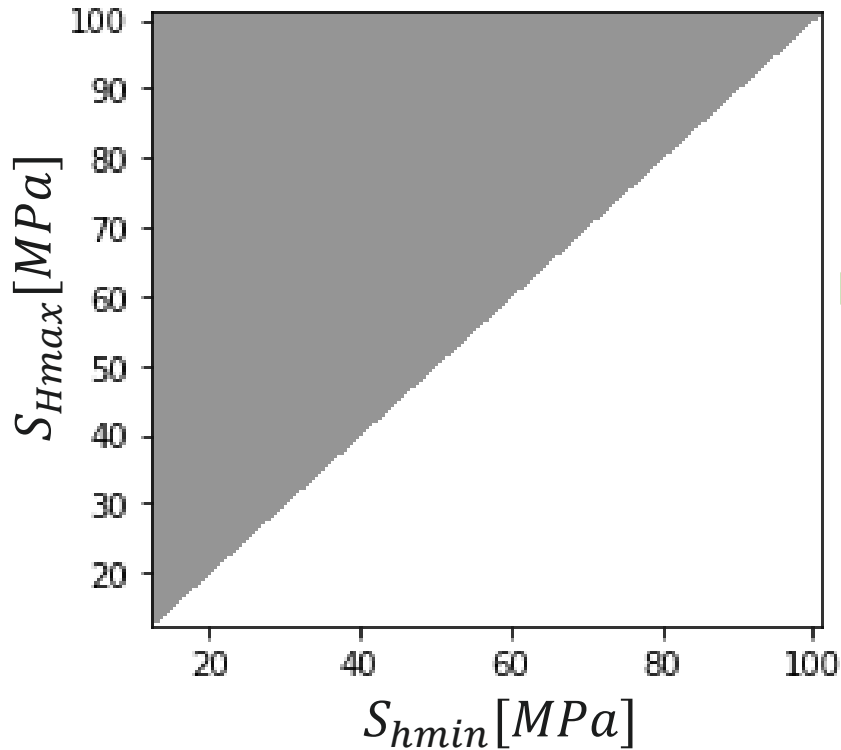
Bayes' theorem



Joint posterior distribution from observations

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

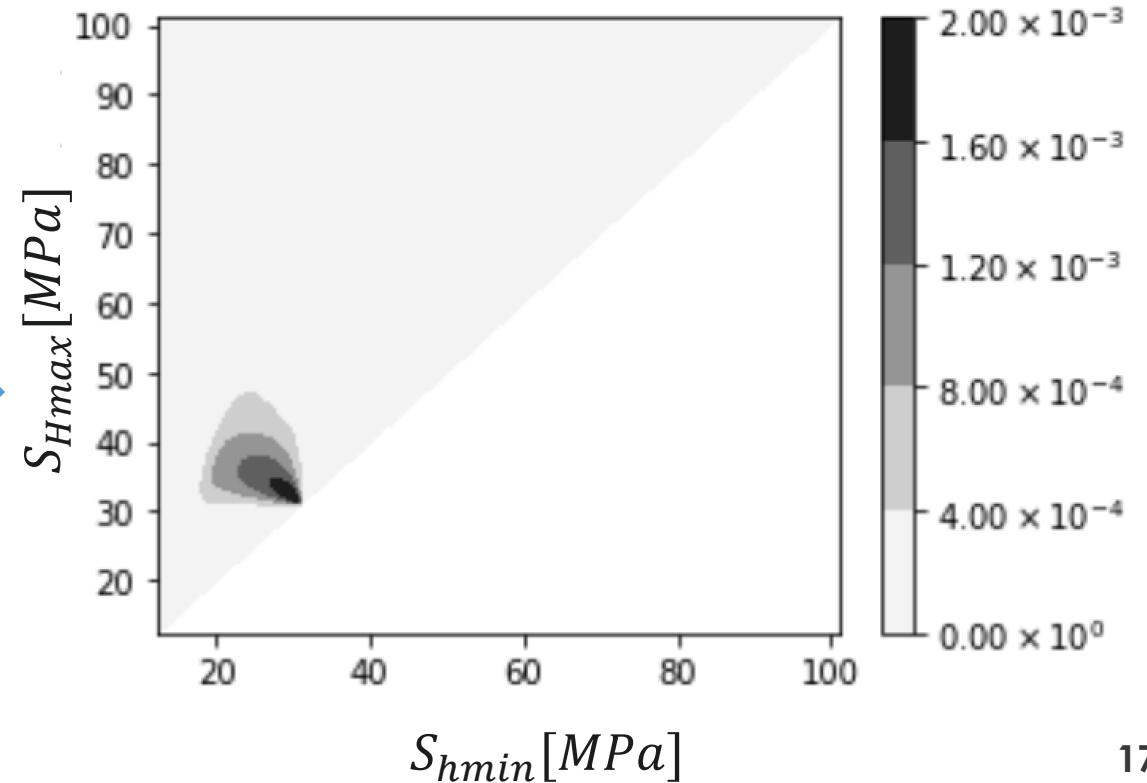
$$\Pi_0(S_H, S_h) = \begin{cases} 1, & \text{if } S_{Hmax} \geq S_{hmin} > 0 \\ 0, & \text{otherwise} \end{cases}$$



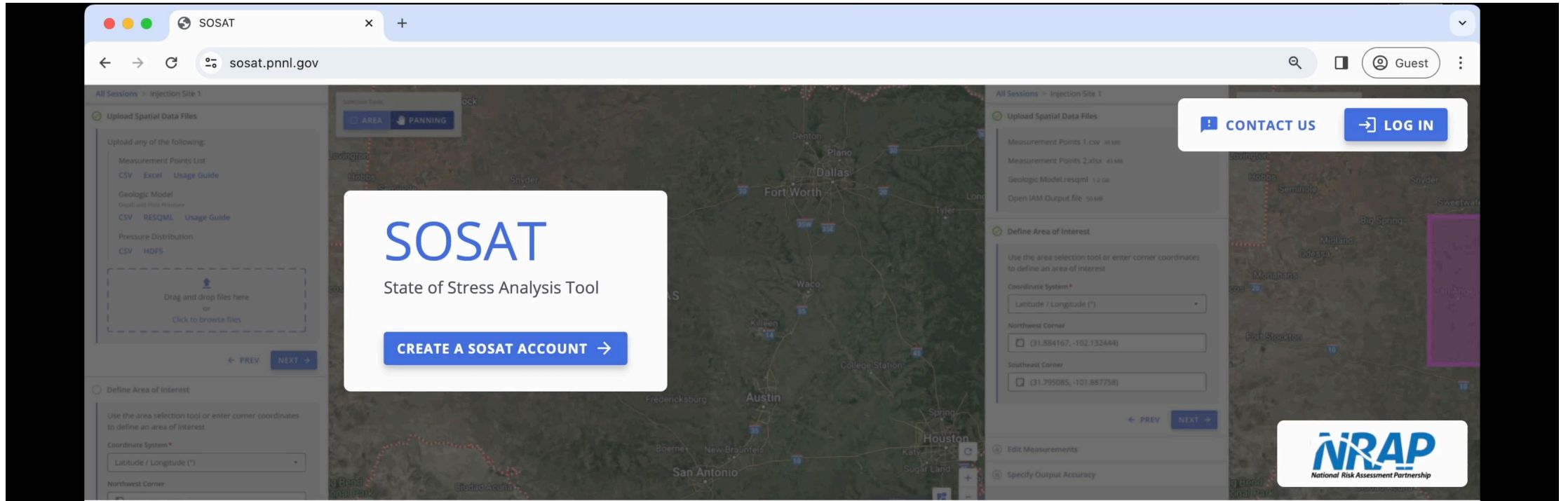
Bayes' theorem



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



SOSAT demo



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

SOSAT

Email or username
wenjing.wang@pnnl.gov

Password [Forgot your password?](#)
.....

Remember me

LOGIN

Need an account? [Send an account request](#)



SOSAT demo

The screenshot displays the SOSAT v1.0.0 web application. The browser address bar shows the URL: `sosat.pnnl.gov/?sessionUUID=7ea4fa28-3f23-4638-8e33-155efdc32c1c&viewing=configuration`. The page title is "SOSAT v1.0.0". In the top right corner, there are links for "DATA PROVENANCE" and the user name "Wenjing Wang".

The main interface is divided into a sidebar on the left and a map area on the right. The sidebar contains the following elements:

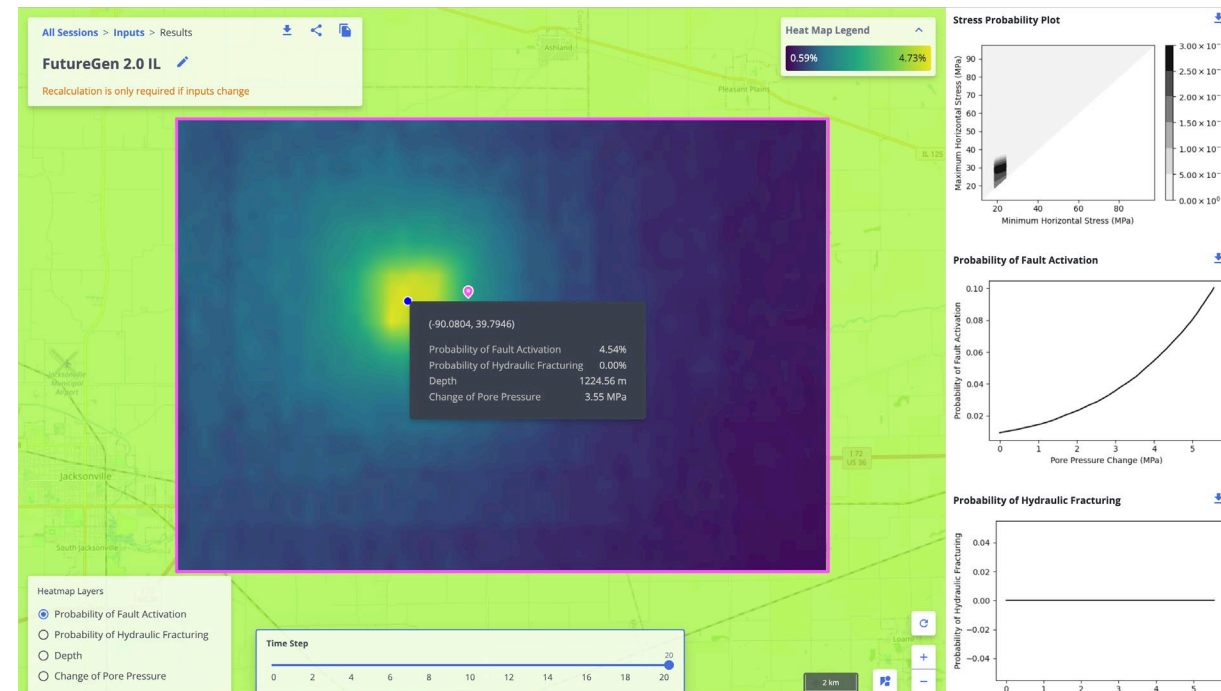
- All Sessions > Inputs**
- Untitled Session** (with an edit icon)
- A green checkmark and the text: "Changes are autosaved."
- Define Area of Interest** (with a checkmark icon)
- Instructions: "Use the area selection tool or enter corner coordinates to define an area of interest"
- Coordinate System *** dropdown menu set to "WGS 84 / Pseudo-Mercator"
- Northwest Corner** input field containing "(-13304852.57, 5872738.05)"
- Southeast Corner** input field containing "(-13321030.74, 5861566.08)"
- A blue "NEXT →" button
- Three radio buttons for: "Review Area Data", "Edit Measurements", and "Specify Calculation Accuracy"

The map area shows a color-coded map of North America, with a color scale for "Relative Stress Magnitude ($A\phi$)" ranging from blue (low stress) to red (high stress). A "Selection Tools" box is overlaid on the map, containing "AREA" and "PANNING" options. A 500 km scale bar is located at the bottom right of the map. The browser's user interface includes standard navigation buttons (back, forward, refresh) and a search icon.

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:

krollwhites1@llnl.gov

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



Disclaimer: This project was funded by the United States Department of Energy, National Energy Technology Laboratory, in part, through a site support contract. Neither the United States Government nor any agency thereof, nor any of their employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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.

