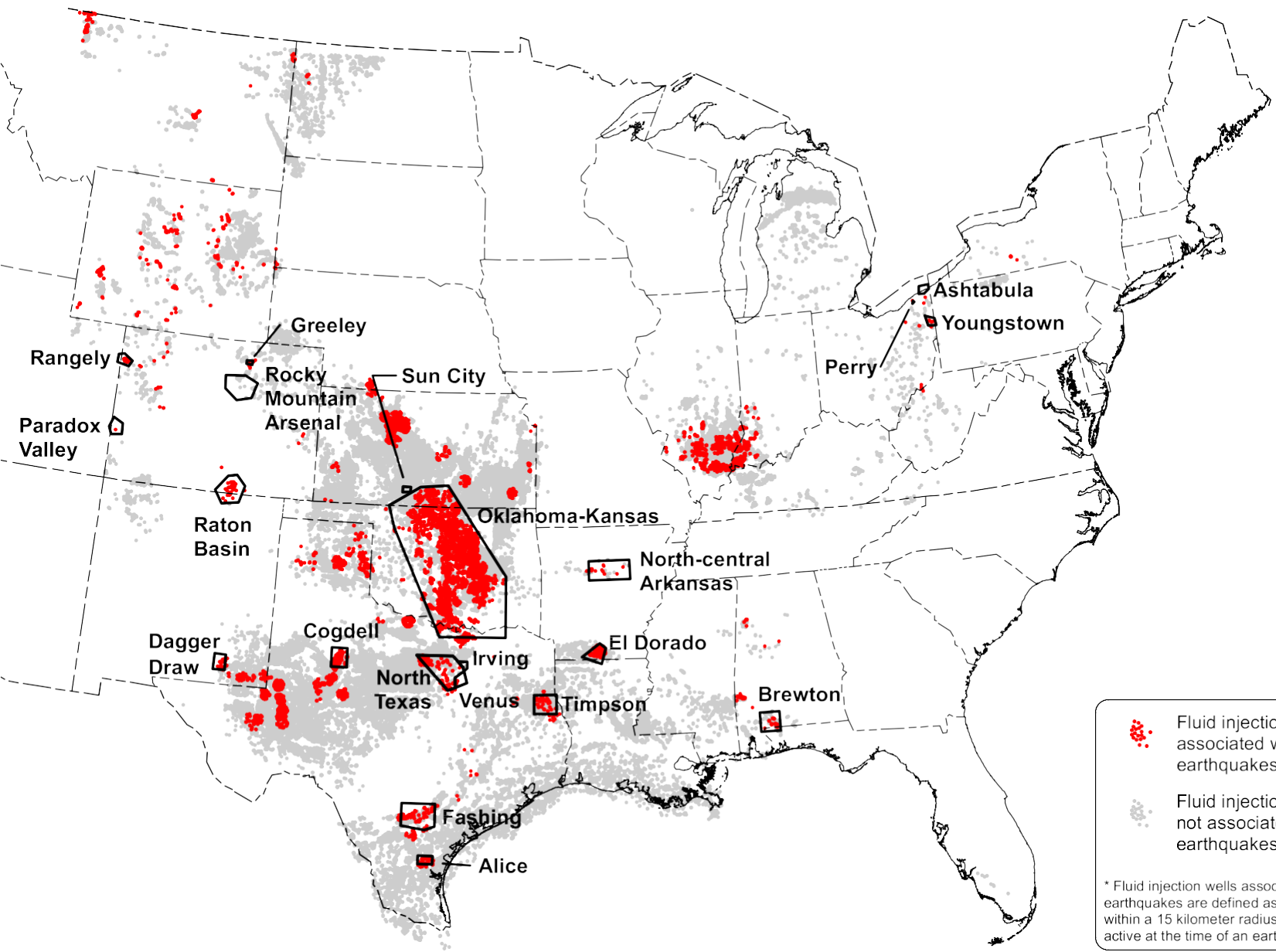


# Task 3: Induced Seismicity Phase II Accomplishments

National Risk Assessment Partnership





**Figure:** USGS map of 21 areas impacted by induced earthquakes

## Phase II: Task 3 Activities

Task	Description
3.1	Real-time hazard forecasting
3.2	Active seismicity management
3.3	Probabilistic seismic risk assessment
3.4	Fault leakage
3.5	Seismicity management protocol
5 + 6	Overlap activities: field demonstration and key questions

## Working Group

NRAP  
Toolkit

Recommended  
Practices

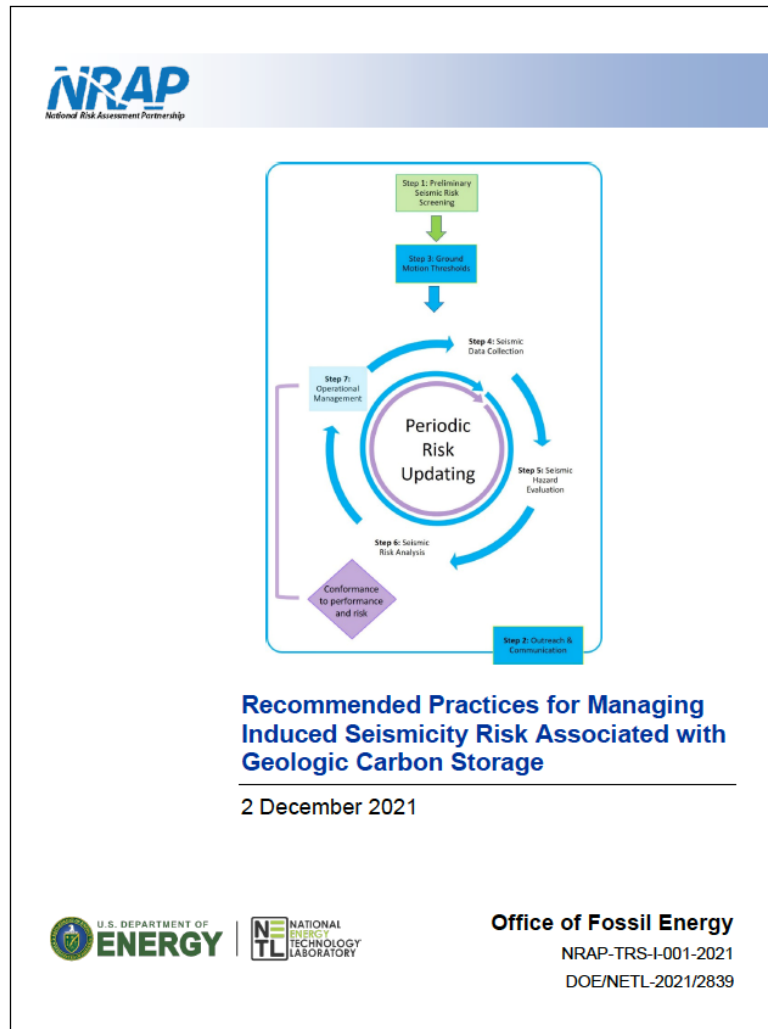
Scientific Basis

- Identify sites and operations that lead to low-risk—i.e. minimal hazard, minimal damage.
- Develop techniques to quickly identify and manage seismicity problems if they should appear.
- Share recommended practices with the broader CCS community

## NRAP Tools, Products, and Capabilities - 2022

Tools	<b>Short-term seismic forecasting tool</b>	Available on EDX
	<b>Ground motion prediction tool</b>	Available on EDX
	<b>State-of-stress assessment tool</b>	Available on EDX
	<b>Probabilistic seismic risk assessment (PSRA) tool</b>	Available on EDX
	<b>ORION: <u>O</u>perational <u>F</u>orecasting of <u>I</u>nduced Seismicity</b>	In Progress
Reports	<b>CO<sub>2</sub> seismic risk assessment review</b>	IJGGC Special Issue
	<b>Numerous technical papers (~20)</b>	NRAP Publication List
	<b>Seismicity Recommended Practices</b>	Available on EDX, publication in review
Capabilities	<b>Induced seismicity simulator (RSQSim)</b>	Mature
	<b>Coupled hydromechanical reservoir simulators</b>	Mature
People	<b>Broad discipline expertise</b>	Seismicity Working Group

# NRAP Recommended Practices for Induced Seismicity



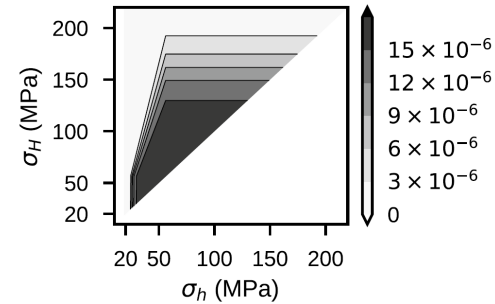
- Step 1** Perform a preliminary screening evaluation.
- Step 2** Implement an outreach and communication program.
- Step 3** Review and select criteria for ground vibration and noise.
- Step 4** Establish seismic monitoring.
- Step 5** Quantify the hazard from natural and induced seismic events.
- Step 6** Characterize the risk of induced seismic events.
- Step 7** Develop risk-based mitigation plan.

# State-of-Stress Assessment Tool (SOSAT)

## Input data available

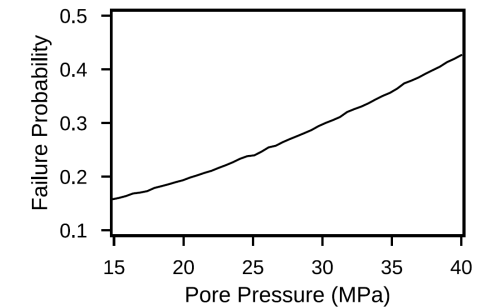
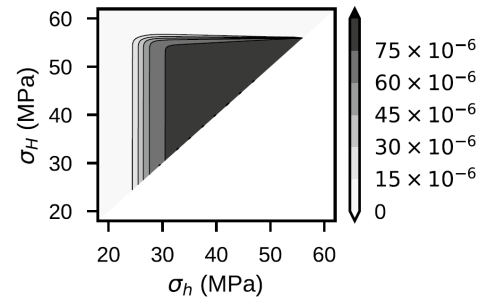
- Pore pressure
- Overburden density

## Joint probability for $\sigma_H$ and $\sigma_h$

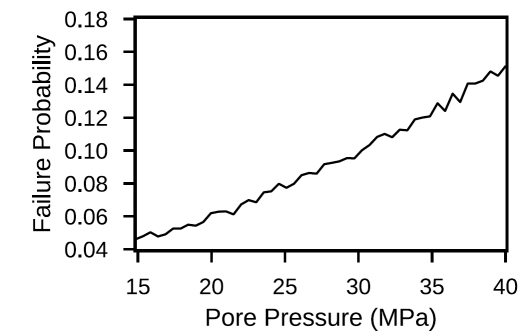
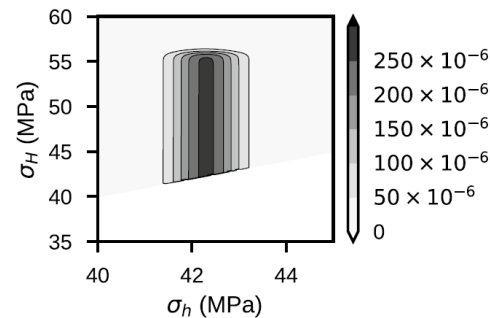


## Probability of activating critically-oriented fault

- Regional stress indicators
- Geodetic data



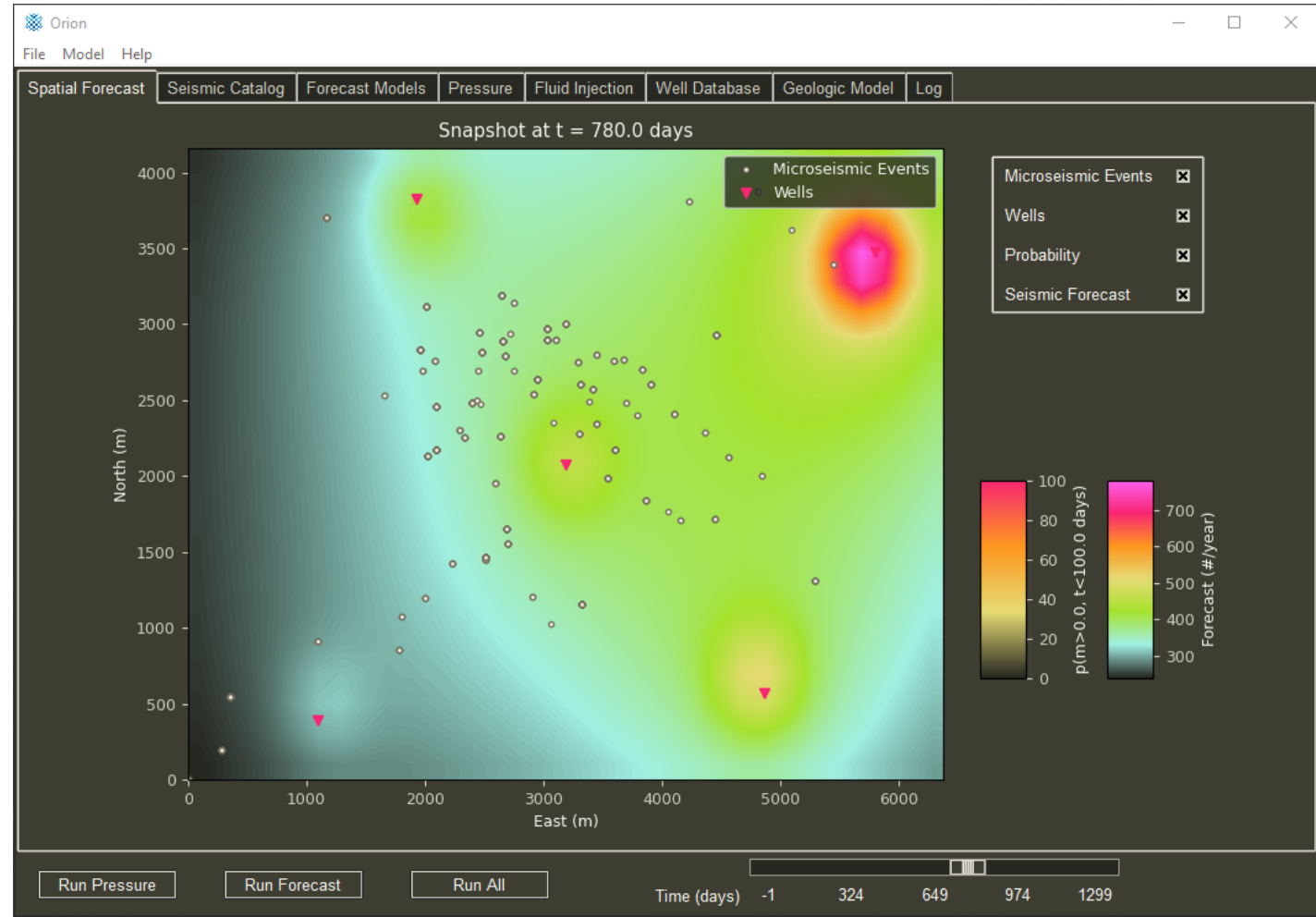
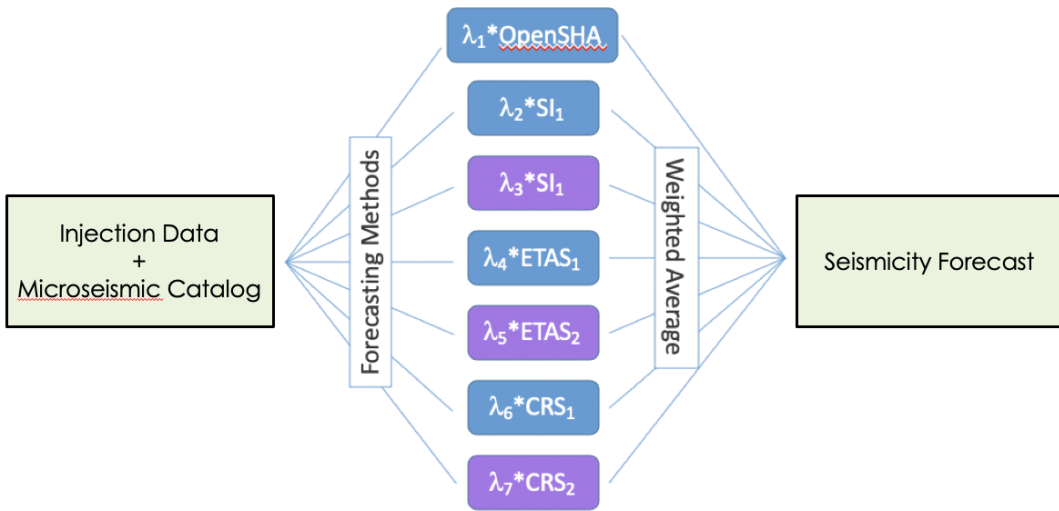
- Local measurement of  $\sigma_h$



# State-of-Stress Assessment Tool (SOSAT)

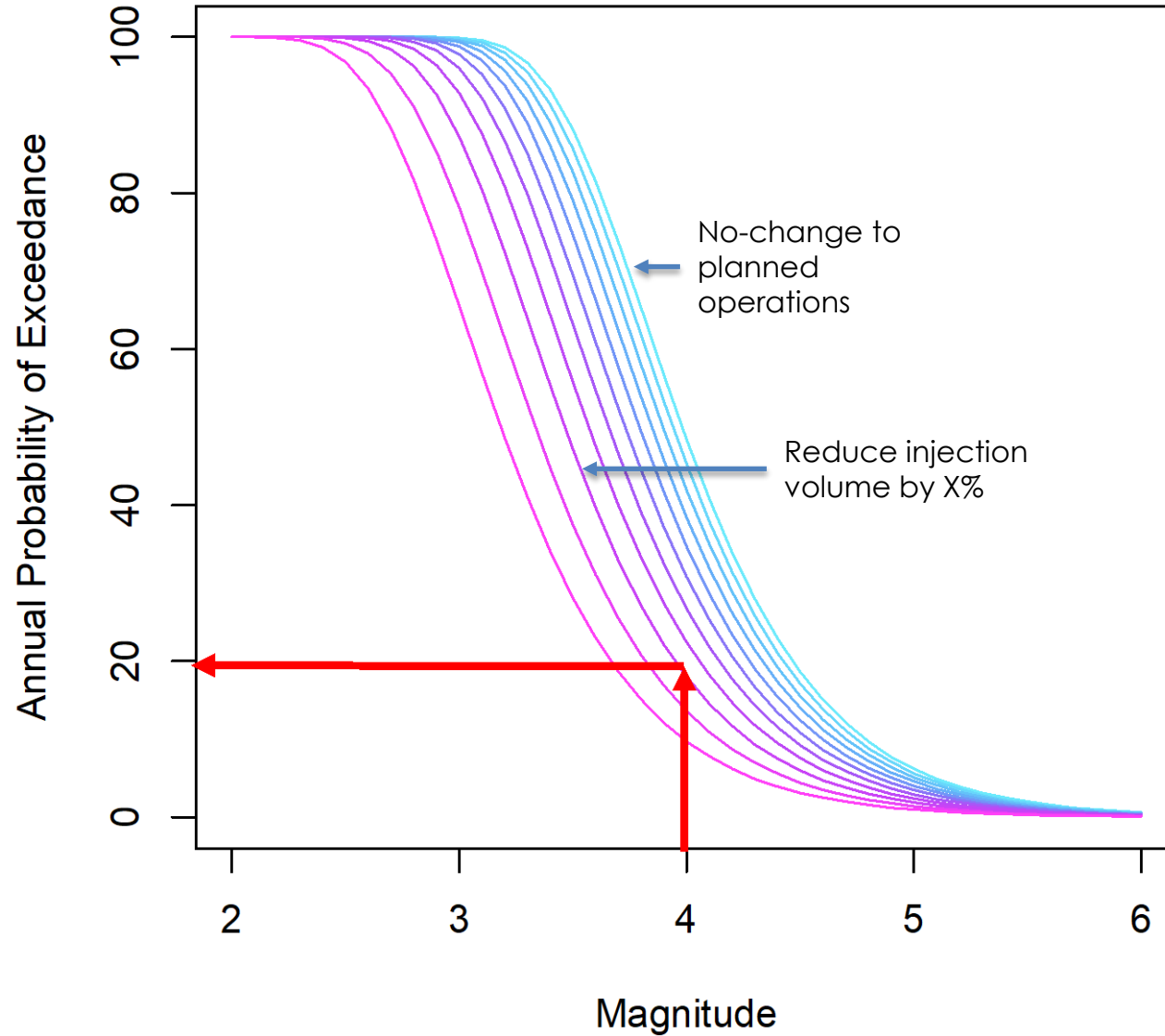
- SOSAT applied at several CarbonSAFE and Partnership sites
  - Southwest Regional Partnership's Farnsworth Site
  - Midwest Regional Carbon Initiative
  - Mid-Continent Stacked Carbon Storage HUB
  - Illinois (Wabash)
- Notable improvements
  - Hosted on Gitlab with Continuous Integration
  - Simplified python package deployment
  - New features

# ORION: Operational Forecasting Of Induced Seismicity

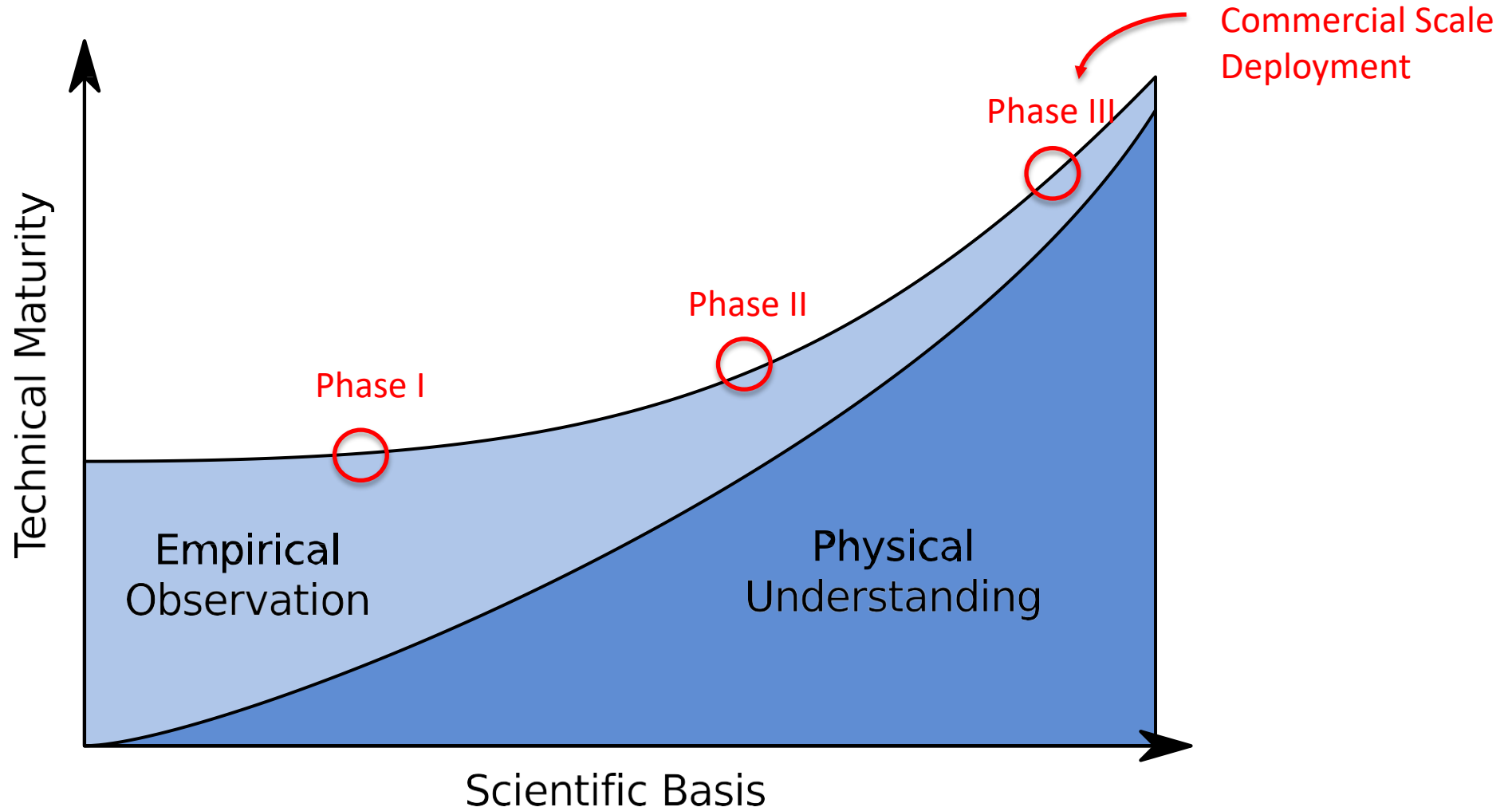




# Short-Term Seismic Forecasting Models



# Phase III perspective plan



## Phase III: Task 3 Basin-scale Activities

Task	Description
3.1	Real-time hazard forecasting
3.2	State-of-stress Analysis
3.3	Fault leakage ROM
3.4	Integration w/NRAP tools

## Working Groups

NRAP  
Toolkit

Recommended  
Practices

Scientific Basis

## Goals

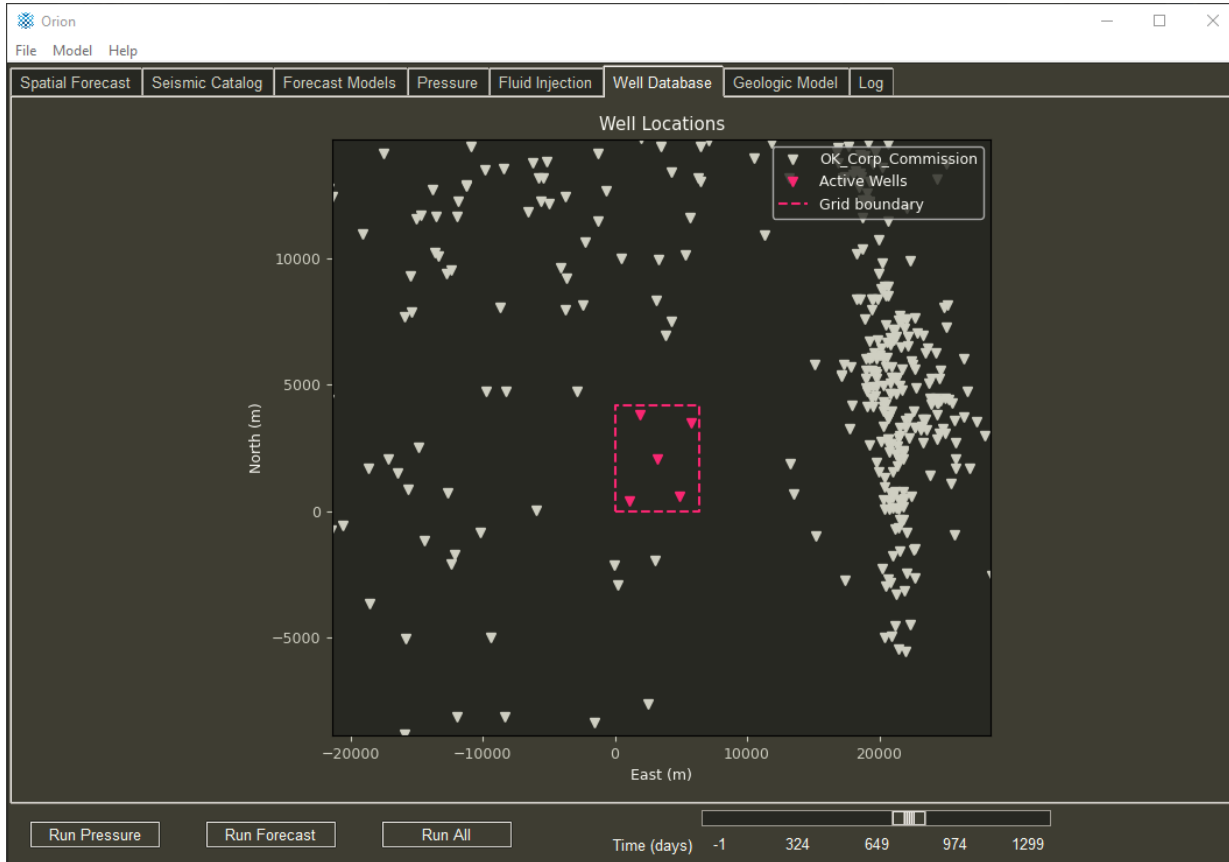
- Identify sites and operations that lead to low-risk—i.e. minimal hazard, minimal damage.
- Develop techniques to quickly identify and manage seismicity problems if they should appear.
- Share recommended practices with the broader CCS community

# NRAP Tools, Products, and Capabilities - 2026

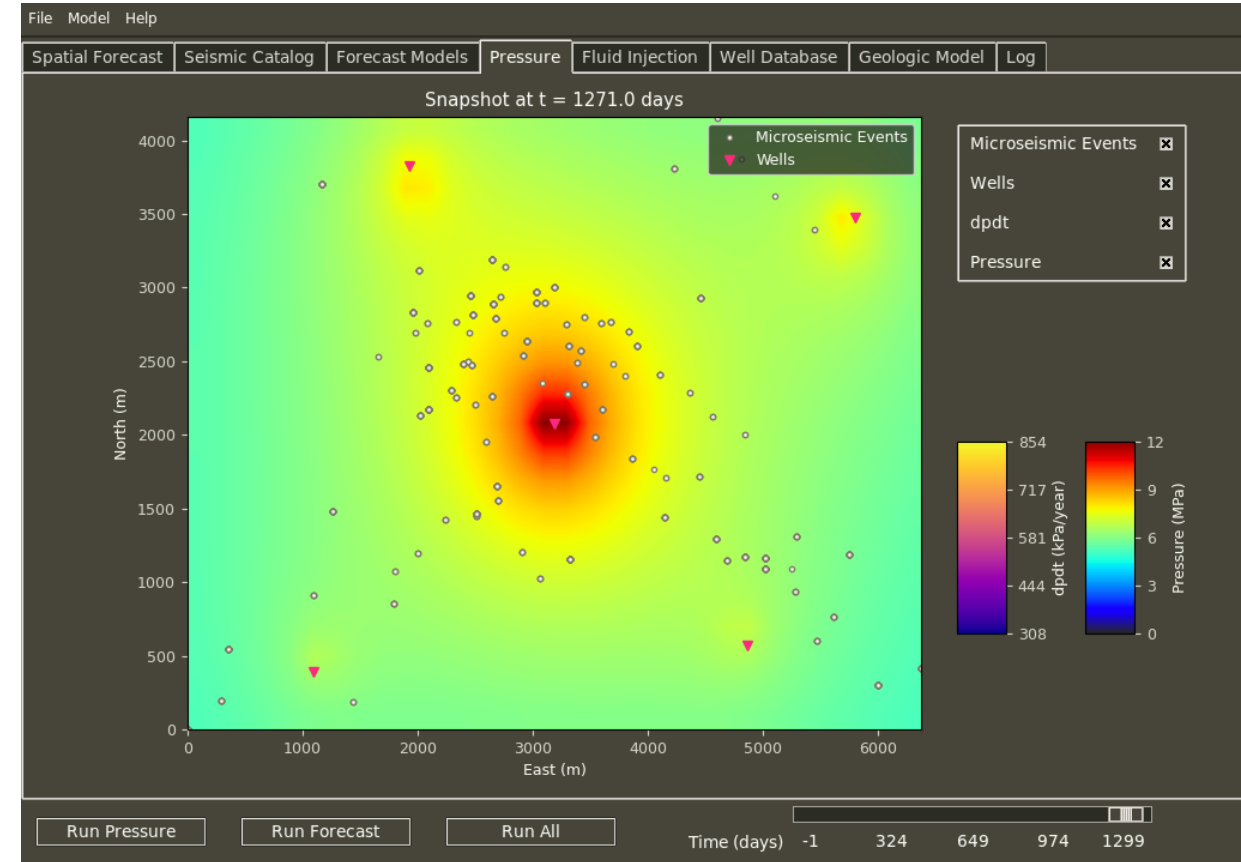
Tools	<b>ORION: <u>O</u>perational <u>F</u>orecasting <u>o</u>f <u>I</u>nduced Seismicity</b>	Version 1.0
	<b>State-of-stress assessment tool</b>	Version 2.0
	<b>Fault Leakage Reduced Order Model</b>	Version 1.0
Reports	<b>State-of-Stress Evaluation Recommended Practices</b>	Version 1.0
	<b>Seismicity Recommended Practices</b>	Version 2.0
	<b>Technical report (~3) and peer reviewed publications (~5)</b>	NRAP Publication List
Capabilities	<b>Induced seismicity simulator (RSQSim)</b>	Mature
	<b>Coupled hydromechanical reservoir simulators</b>	Mature
People	<b>Broad discipline expertise</b>	Seismicity Working Group

# Basin Scale forecasts

Oklahoma Injection Well Database

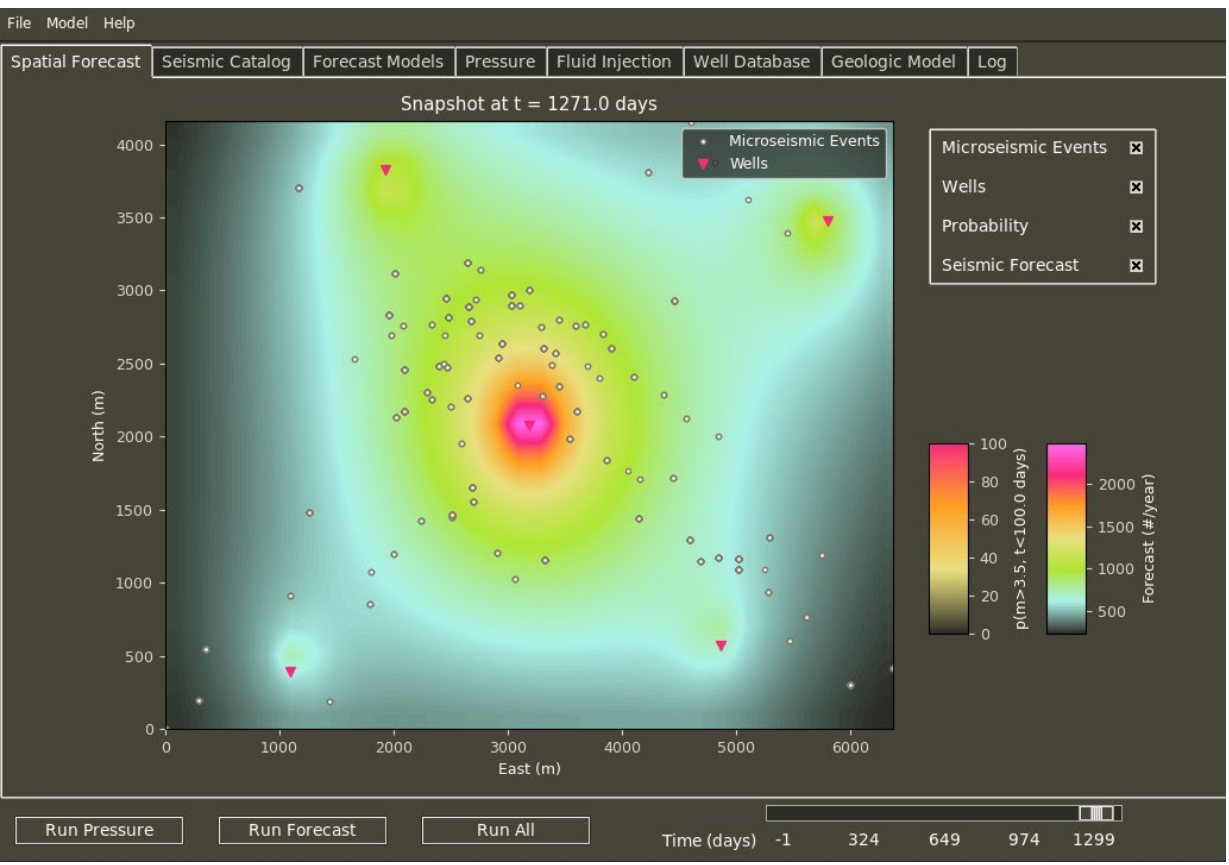


Reservoir Pressure

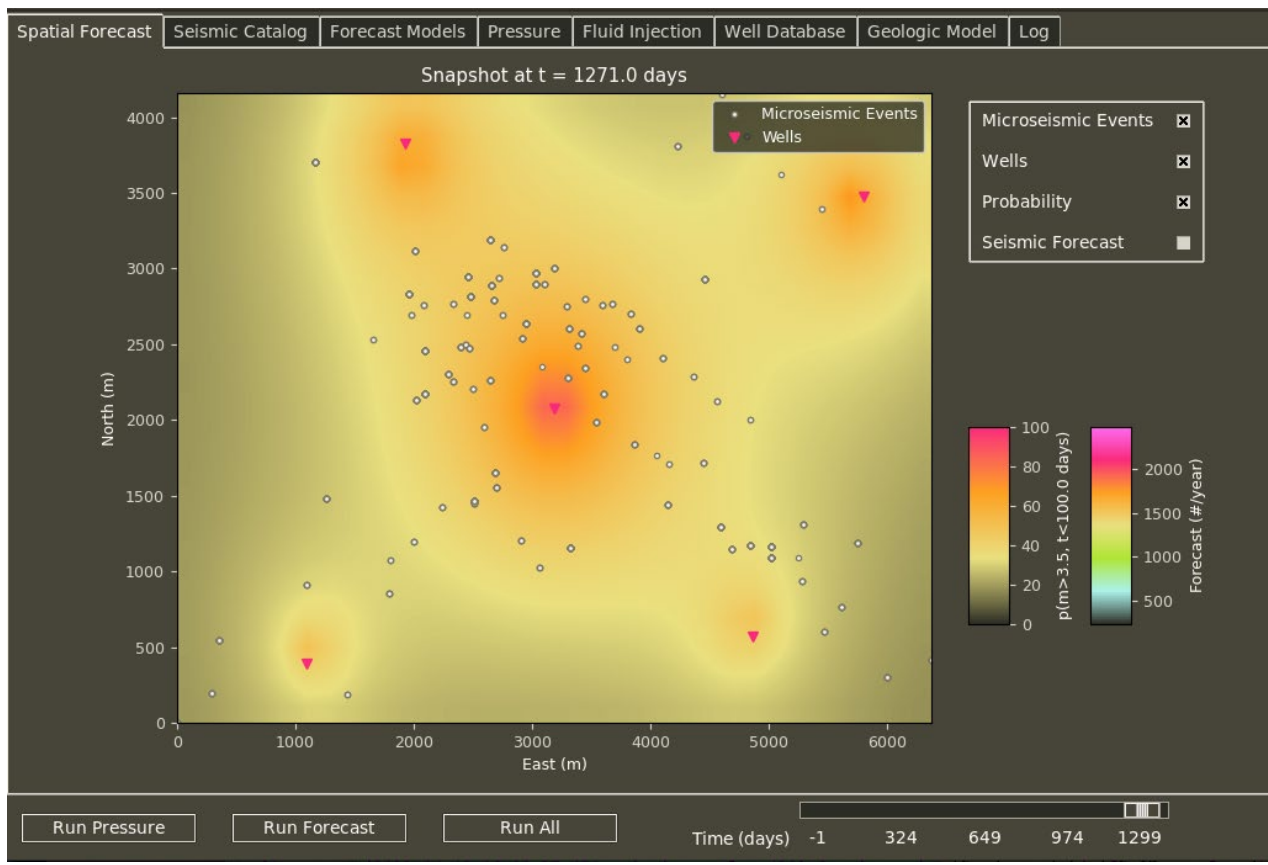


# Spatial forecasts

### Number of events

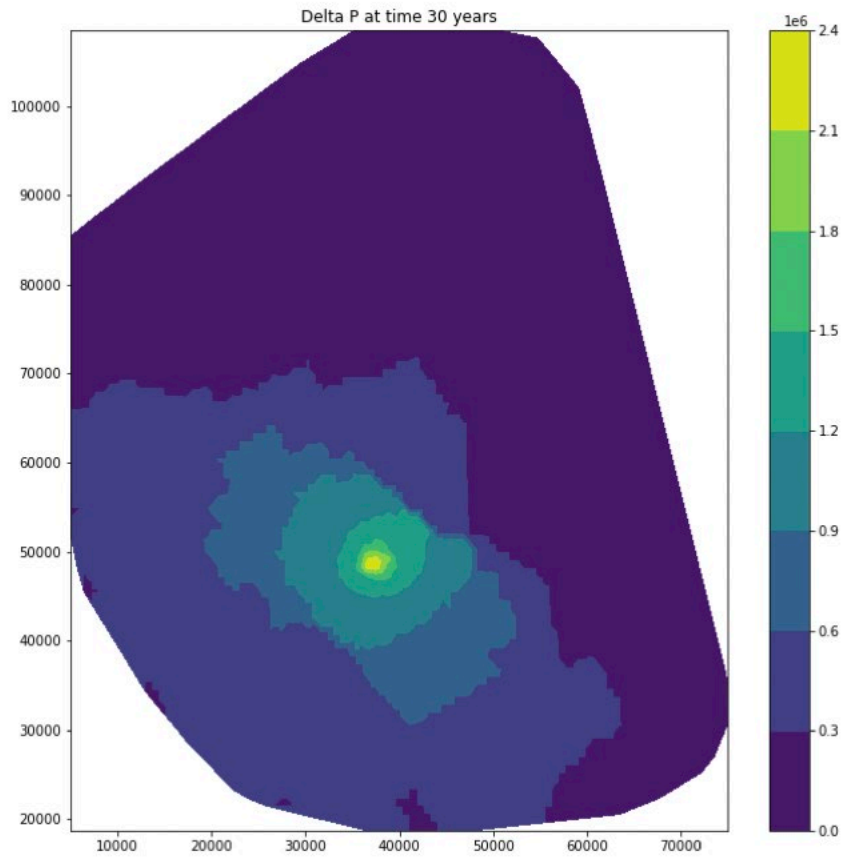


### Probability of Exceedance

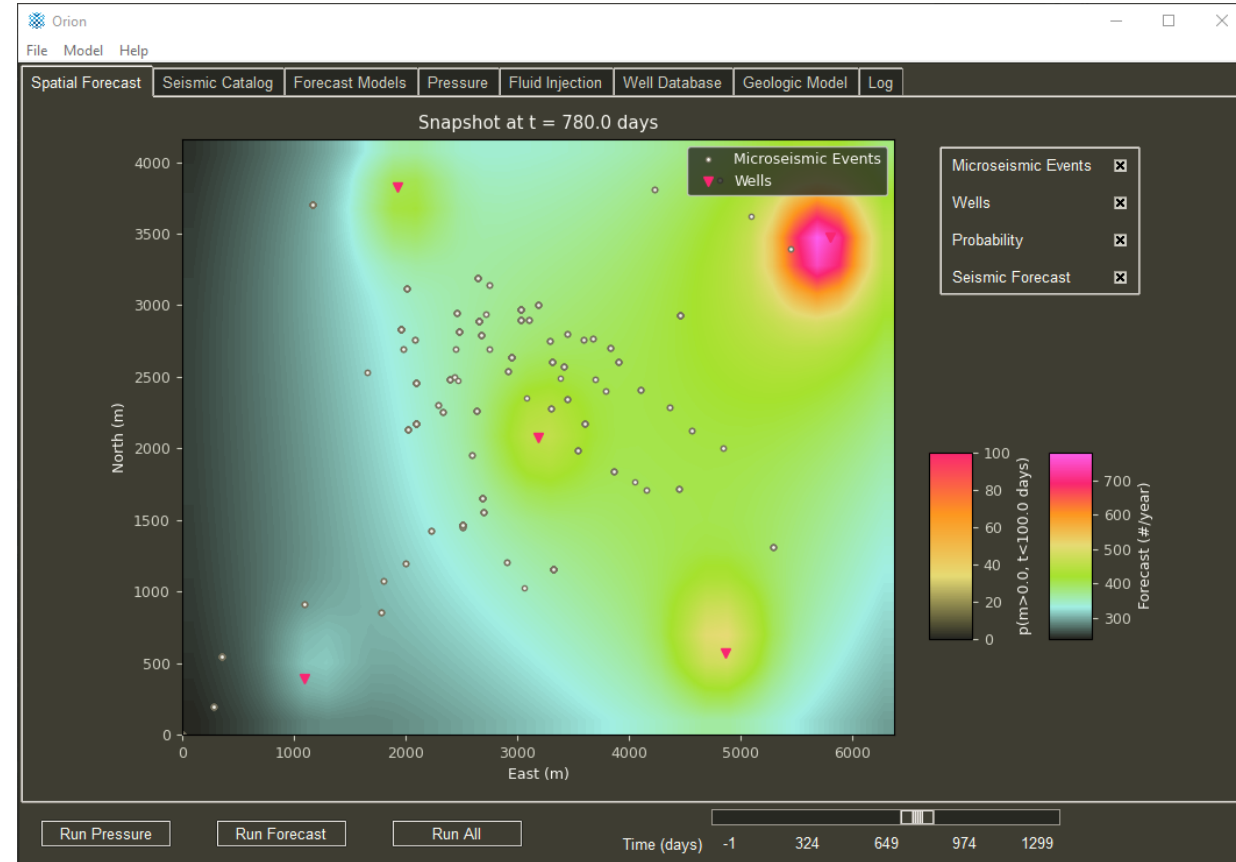


# Integration with OpenIAM

Reservoir Pressure from OpenIAM

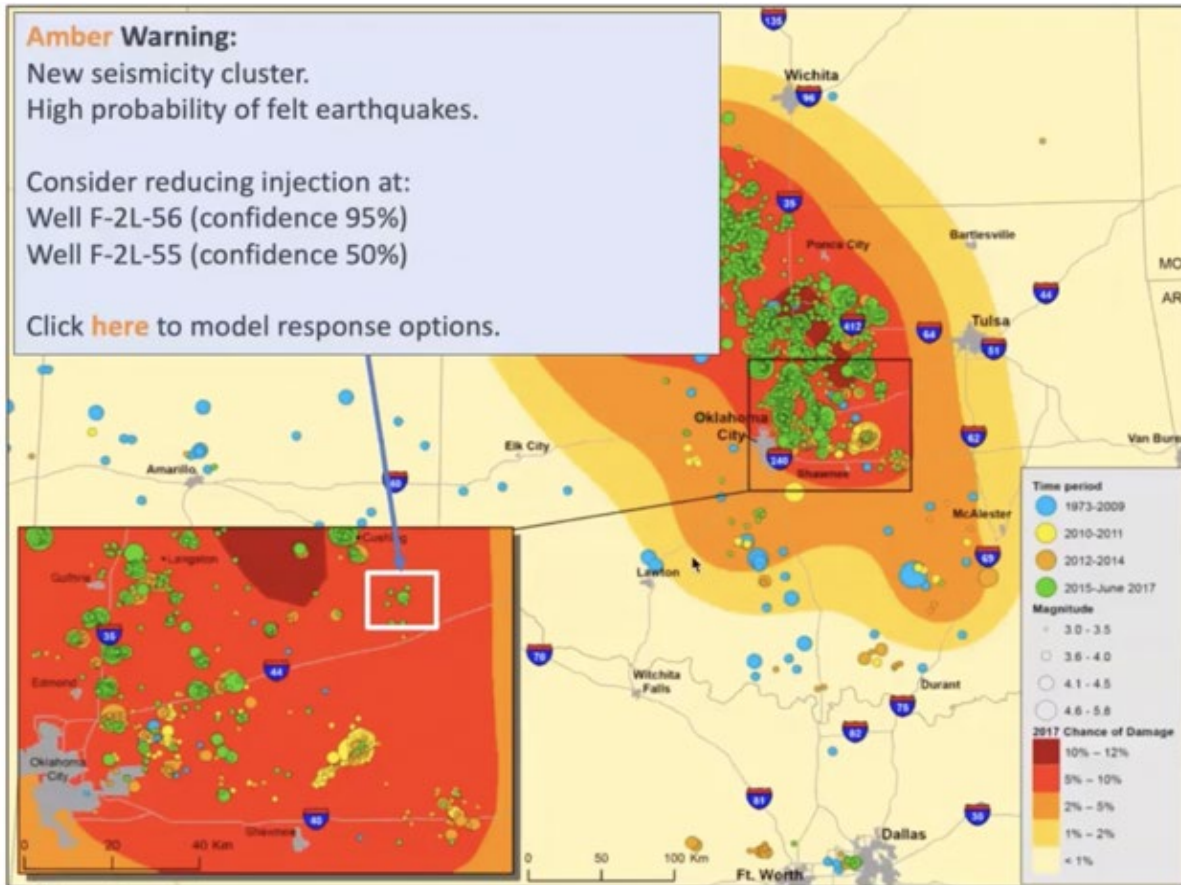


Number of events

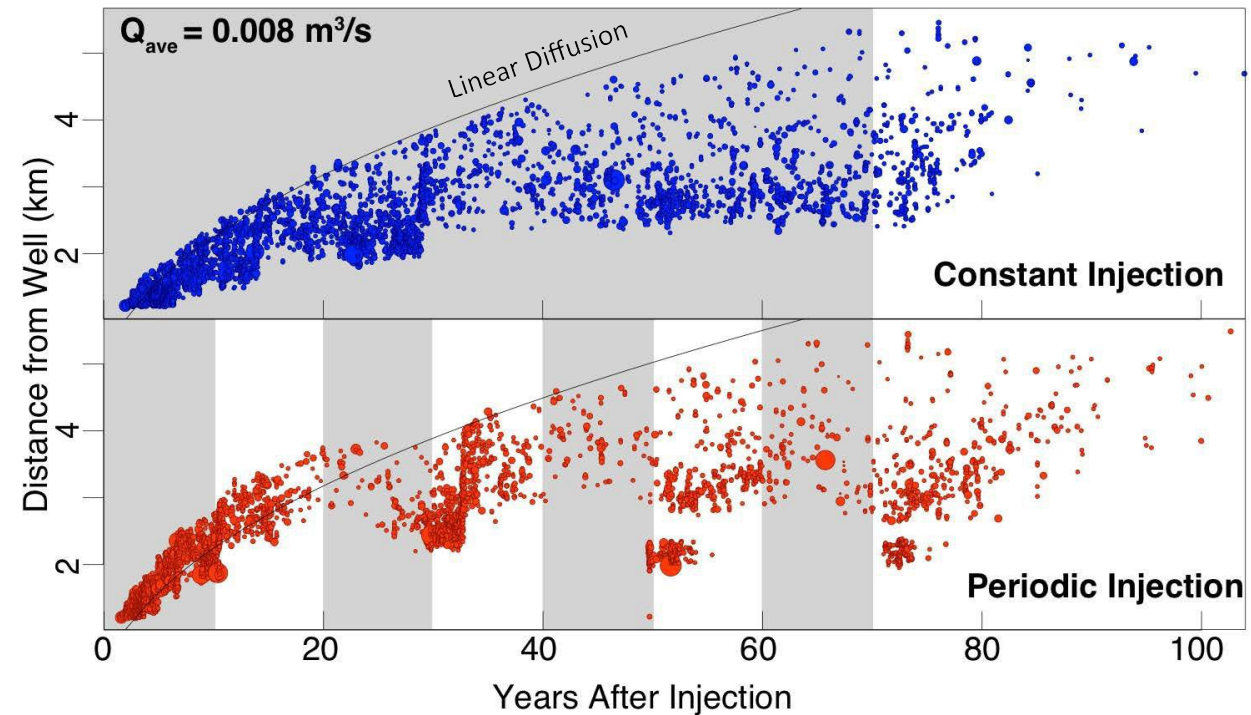


# Operational management strategies

Issue alert with modified injection strategy



Improved scientific understanding of efficacy



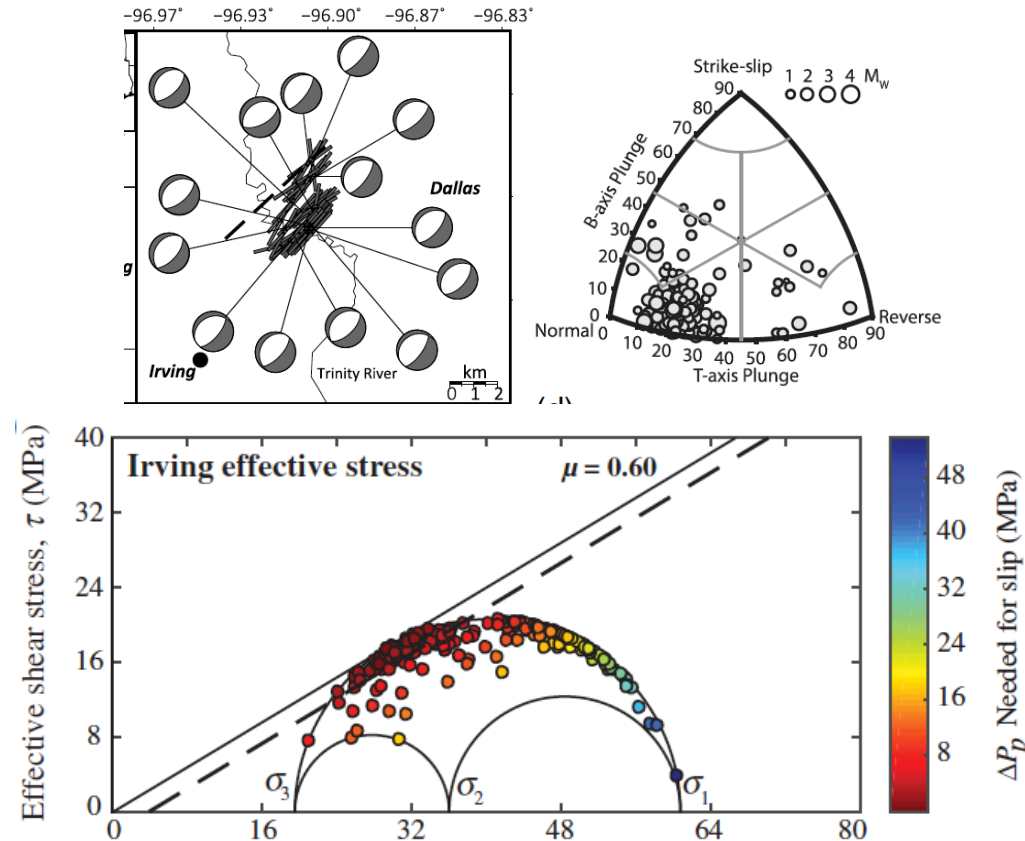


# State-of-Stress Assessment Tool (SoSAT v2.0)

## v1.0 Input data

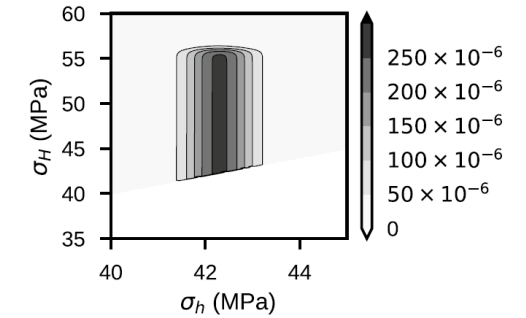
- Pore pressure
- Overburden density
- Regional stress indicators
- Geodetic data
- Local measurement of  $\sigma_h$

## v2.0 Input Data: v1.0 input + focal mechanisms

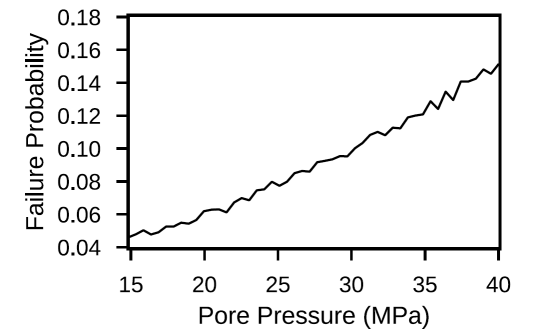


Quinones et al., 2018

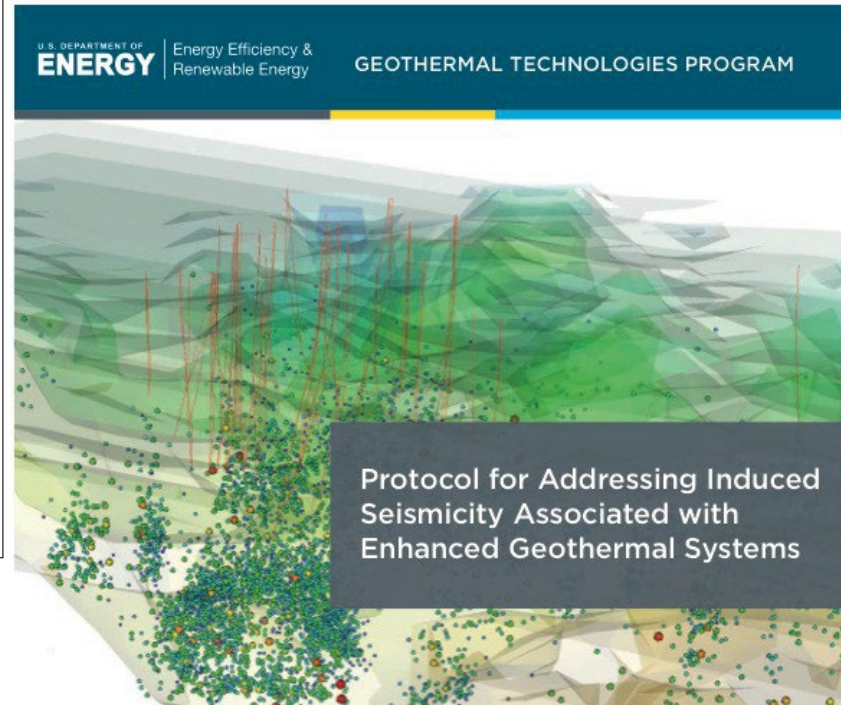
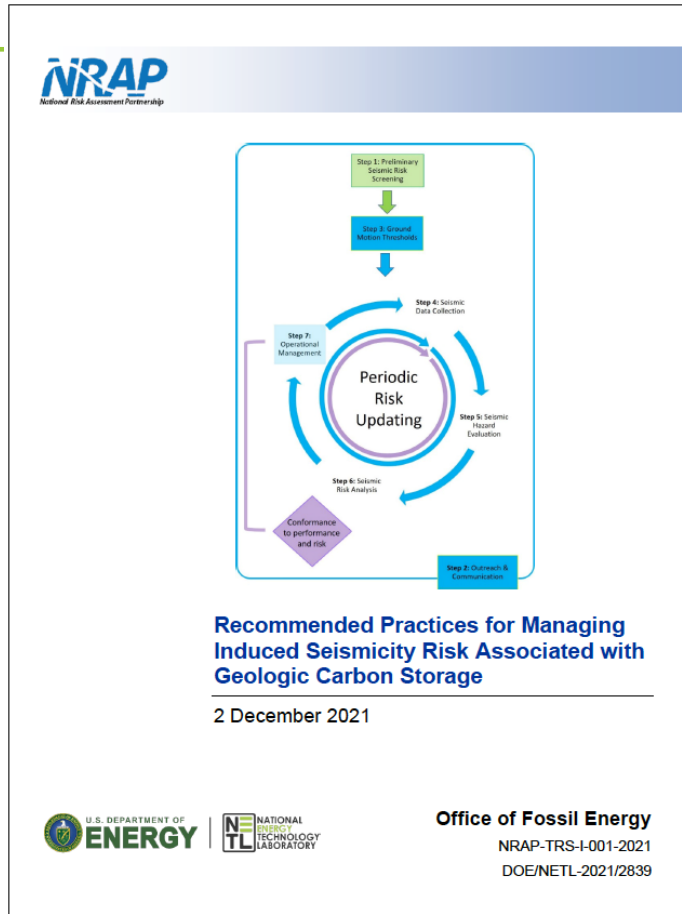
## Joint probability for $\sigma_H$ and $\sigma_h$



## Probability of activating critically-oriented fault

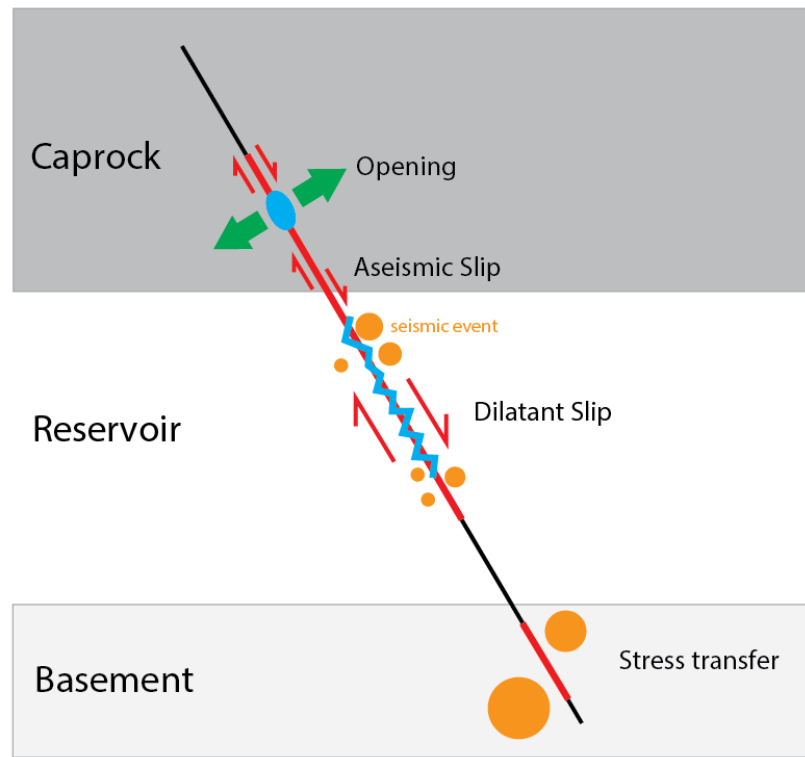


# State-of-Stress Evaluation Recommended Practices



- **Starting Point:**
  - NRAP Induced Seismicity Recommended Practices
  - GTO Geothermal Seismicity Protocol (2012).
  
- **Goal:** Develop recommended practices guidelines relevant for stress state evaluation in carbon storage settings

# Improved Fault leakage ROM



- Slip trigger
  - Discrete pressurized leakage zone
  - Mainly aseismic reactivation and creep
  - Low friction-vs-velocity dependence at high P
  - Long-term sealing
- 
- Pressure trigger
  - Distributed pressurized leakage zone
  - Seismic reactivation with some aseismic component
  - High friction-vs-velocity dependence even at high P

Y. Guglielmi, C. Nussbaum, F. Cappa, L. de Barros, J. Rutqvist and J. Birkholzer (2021). *Field-scale fault reactivation Experiments by fluid injection highlight aseismic leakage in caprock analogs: Implications for CO<sub>2</sub> sequestration* *International Journal of Greenhouse Gas Control* 111 (2021) 103471.

# NRAP Tools, Products, and Capabilities - 2026

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