National Risk Assessment Partnership:

Induced Seismicity Working Group

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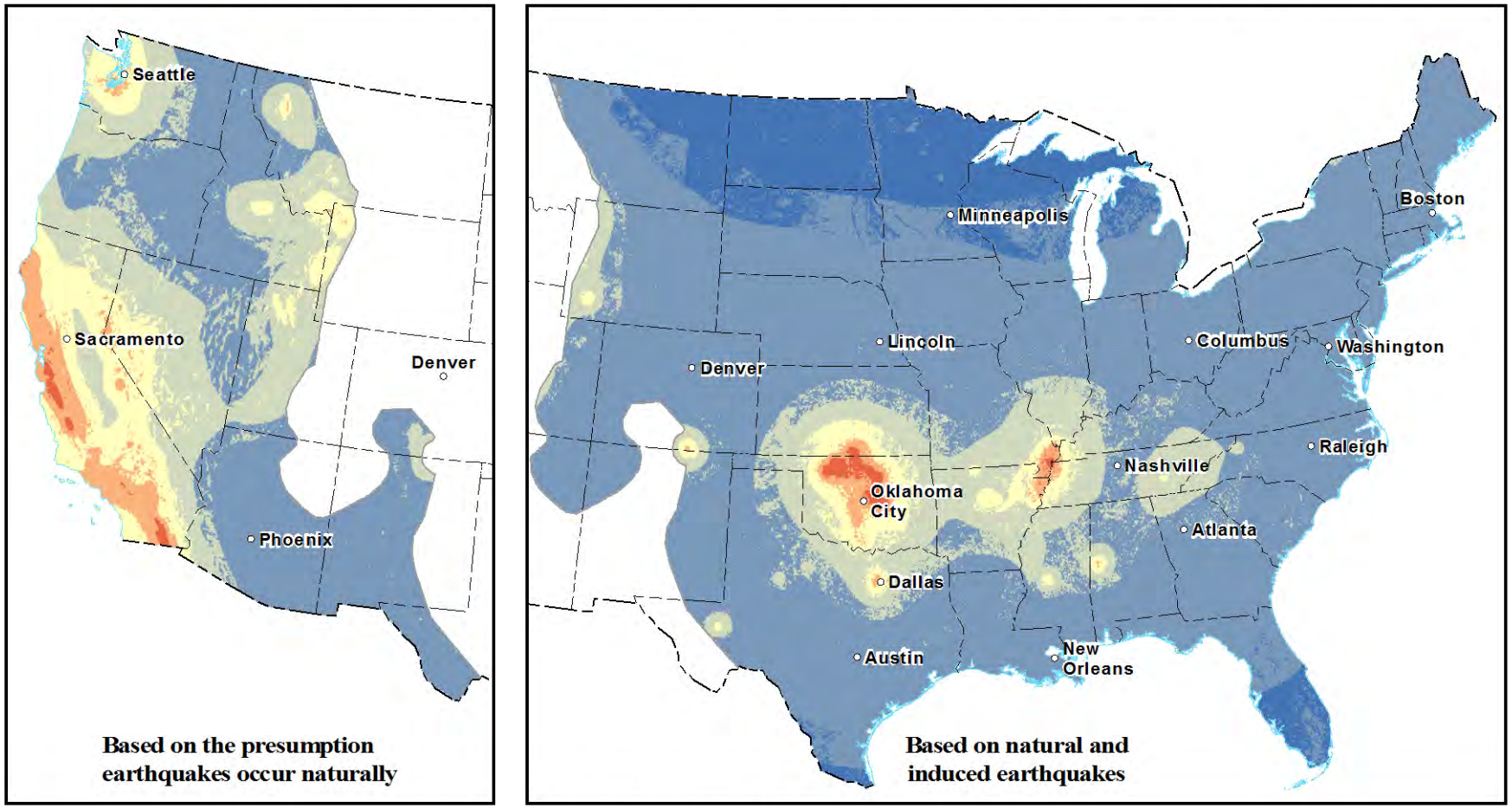
USGS Forecast for Ground Shaking Intensity from Natural and Induced Earthquakes in 2016



Modified Mercalli Intensity

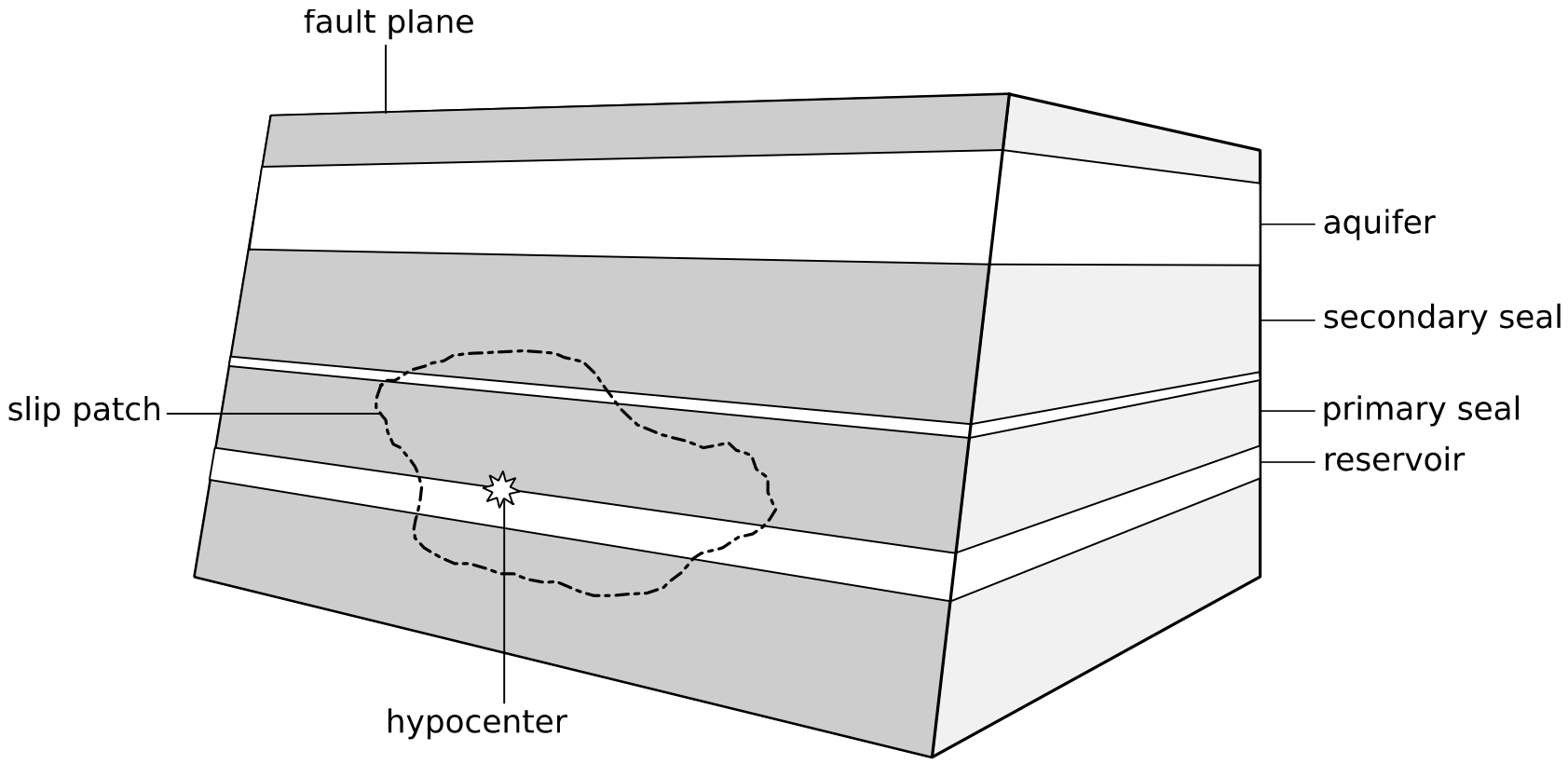
VIII+	Shaking severe, heavier damage
VII	Shaking very strong, moderate damage
VI	Shaking strong, felt by all, minor damage
V	Shaking moderate, felt indoors by most, outdoors by many
IV	Shaking light, felt indoors by many, outdoors by few
III	Shaking weak, felt indoors by several

USGS map displaying intensity of potential ground shaking from natural and human-induced earthquakes. There is a small chance (one percent) that ground shaking intensity will occur at this level or higher. There is a greater chance (99 percent) that ground shaking will be lower than what is displayed in these maps.

[USGS 2016]

Working Group 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.



NRAP Tools, Products, and Capabilities - 2018

Tools	**Short-term seismic forecasting tool**	Available on EDX
	Ground motion prediction tool	Available on EDX
	** **State-of-stress assessment tool**	New / available fall 2018
	** **Probabilistic seismic risk assessment (PSRA) tool**	New / available fall 2018
Reports	**CO_2 seismic risk assessment review paper**	IJGGC Special Issue
	Numerous technical papers	NRAP Publication List
	** **NRAP seismicity protocol and recommended practices**	Planned FY19
Capabilities	**Induced seismicity simulator (RSQSim)**	Mature
	Coupled hydromechanical reservoir simulators	Mature
People	**Broad discipline expertise**	Seismicity Working Group

Significant Accomplishments in FY18

1	Active pressure management study
2	New state-of-stress assessment tool
3	New probabilistic seismic risk assessment tool
4	Numerous journal publications

Testing efficacy of active pressure management as a tool for mitigating seismicity

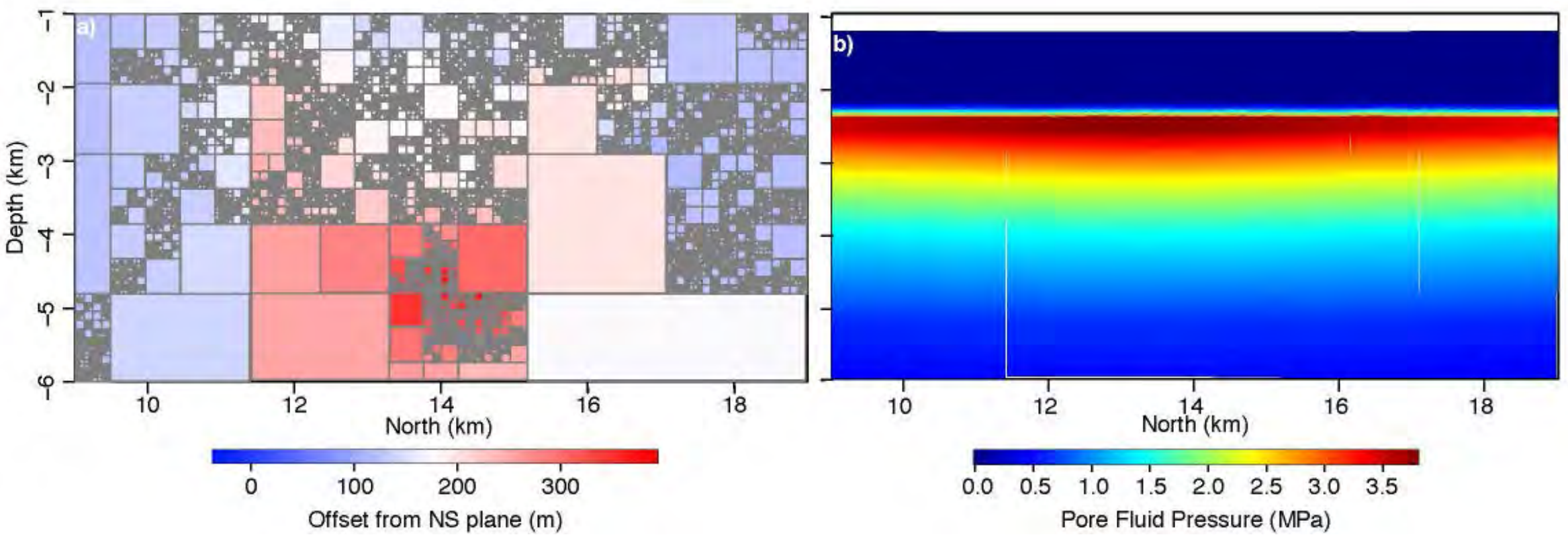


Figure: RSQSim simulation of induced seismicity on a basement fault connected with a CO_2 storage reservoir.

Reference: Kroll et al. (2018, under review).

Testing efficacy of active pressure management as a tool for mitigating seismicity

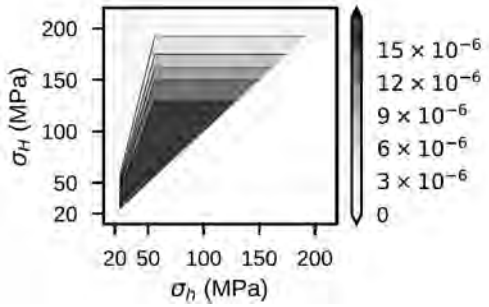
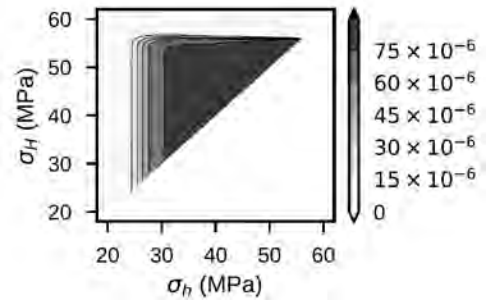
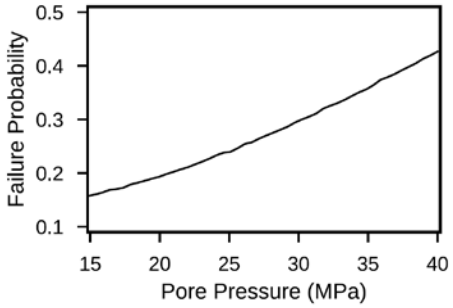
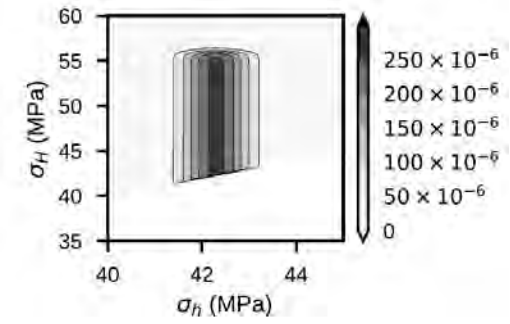
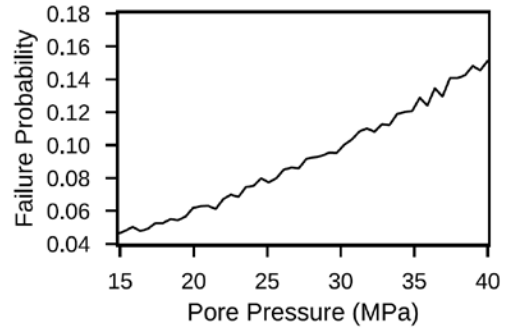
- **Study Conclusion**: Two APM strategies can lead to a reduction in seismic hazard, with significant caveats:

  - **Strategy 1: Maintaining a (near) net balance between injection and production**
    - Keeps overall pressure perturbation low
    - Insensitive to well and fault location
    - Requires managing a huge volume of produced brine

  - **Strategy 2: Producing brine directly on a problematic fault**
    - More targeted, but may still require producing large volumes
    - May not be a reliable approach in the face of geologic uncertainty

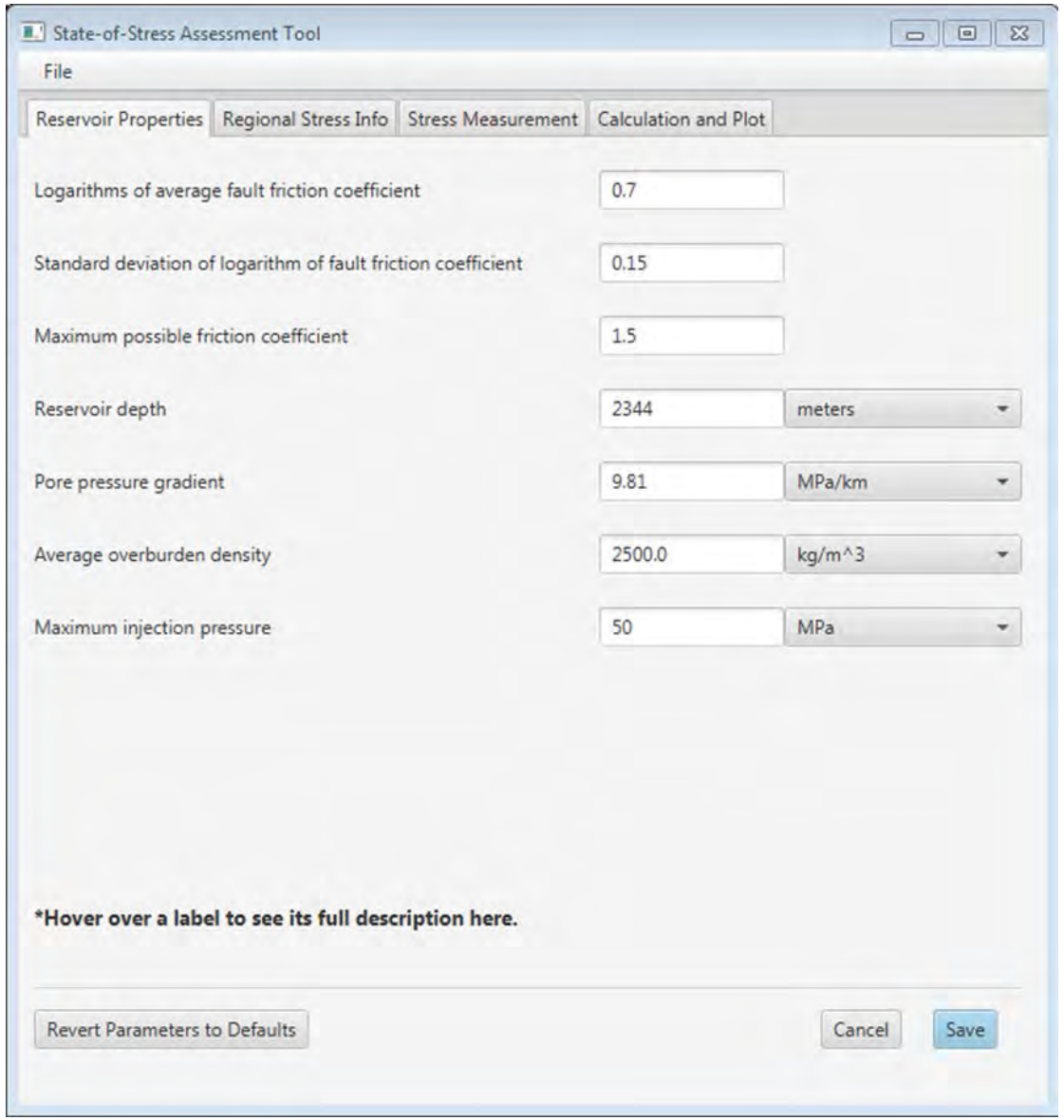
Reference: Kroll et al. (2018, under review).

State-of-Stress Assessment Tool (SOSAT)

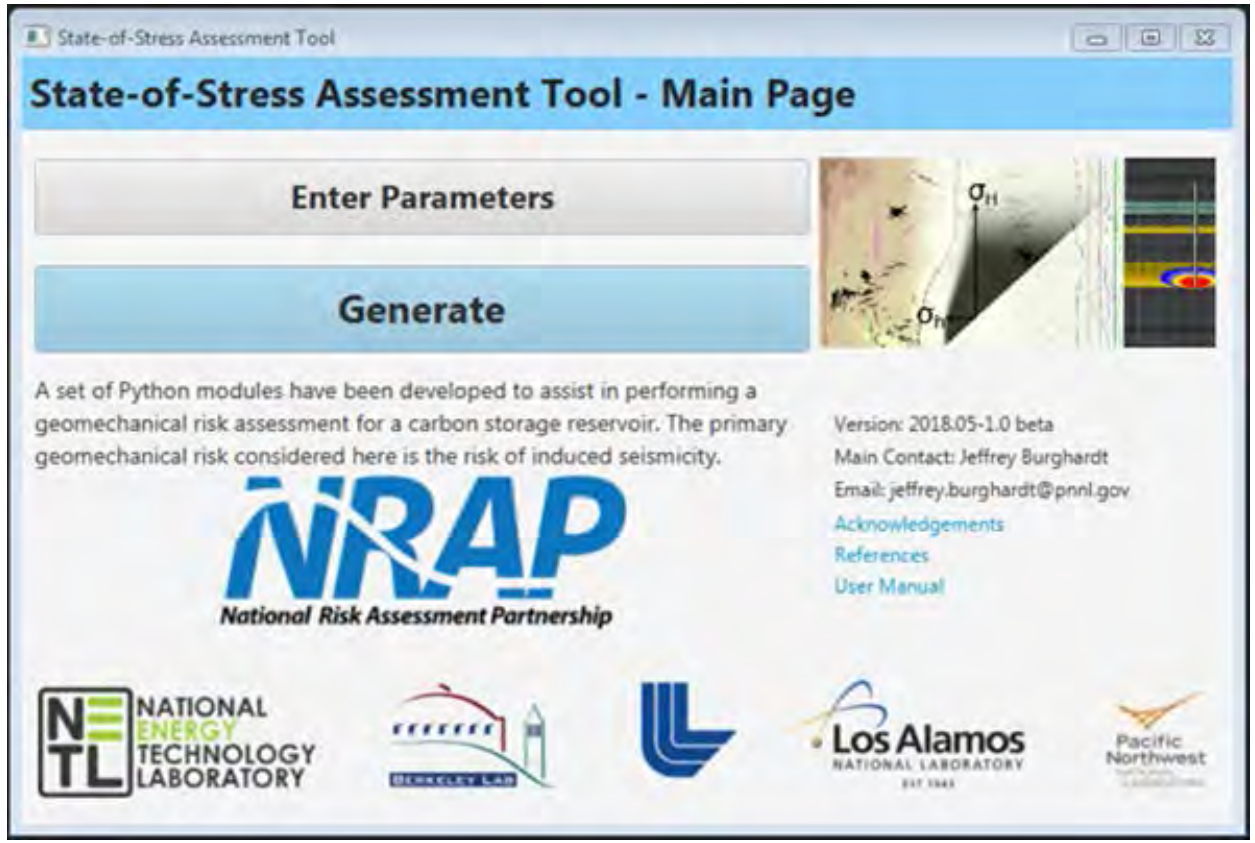
Input data available	Joint probability for σ_H and σ_h	Probability of activating critically-oriented fault
• Pore pressure • Overburden density		
• Regional stress indicators • Geodetic data		
• Local measurement of σ_h		

Reference: Jeff Burghardt (2018) SOSAT User's Manual.

State-of-Stress Assessment Tool (SOSAT)



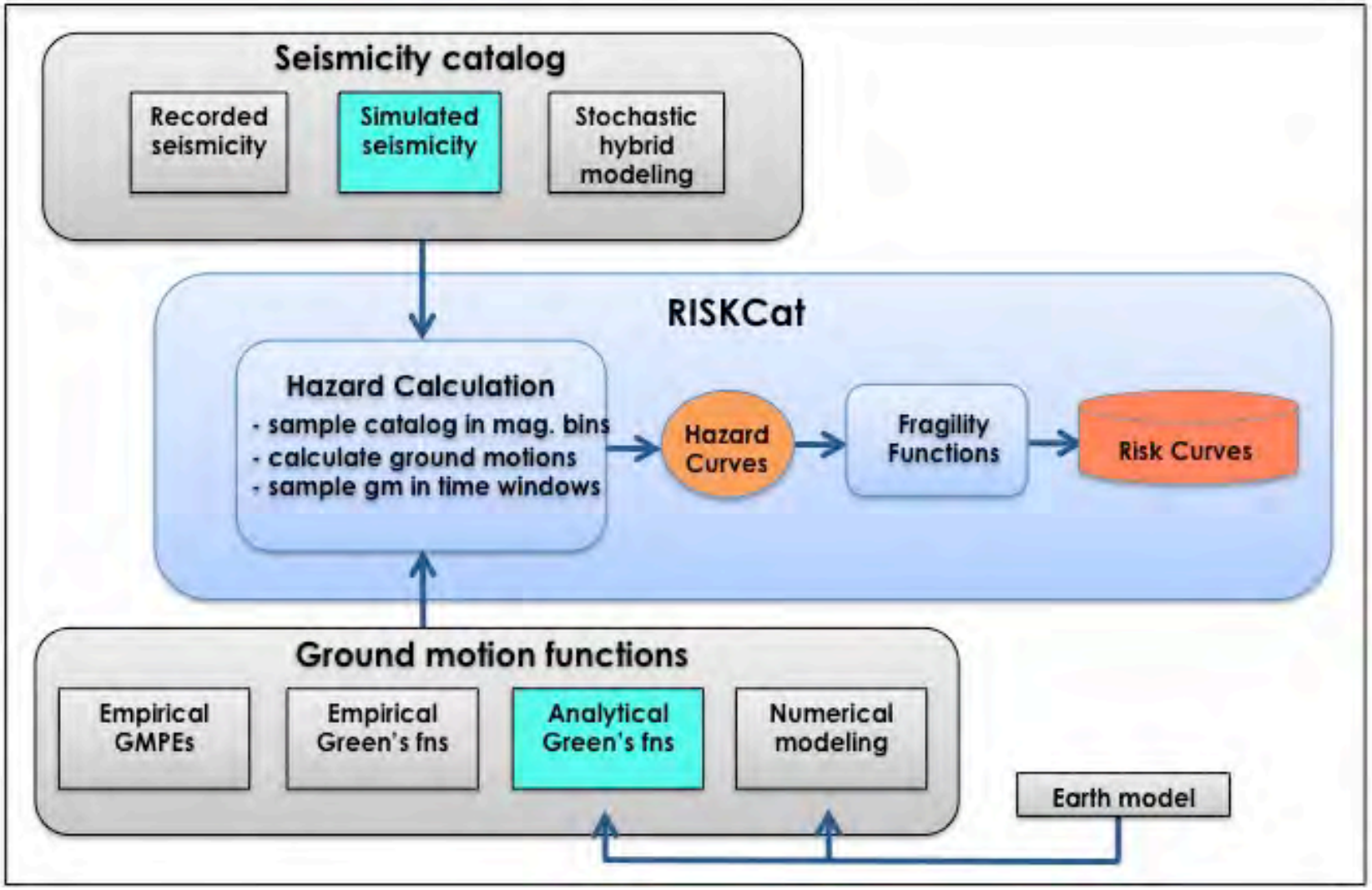
- Tool complete and undergoing internal testing
- Will be beta-released Fall 2018



Reference: Jeff Burghardt (2018) SOSAT User's Manual.

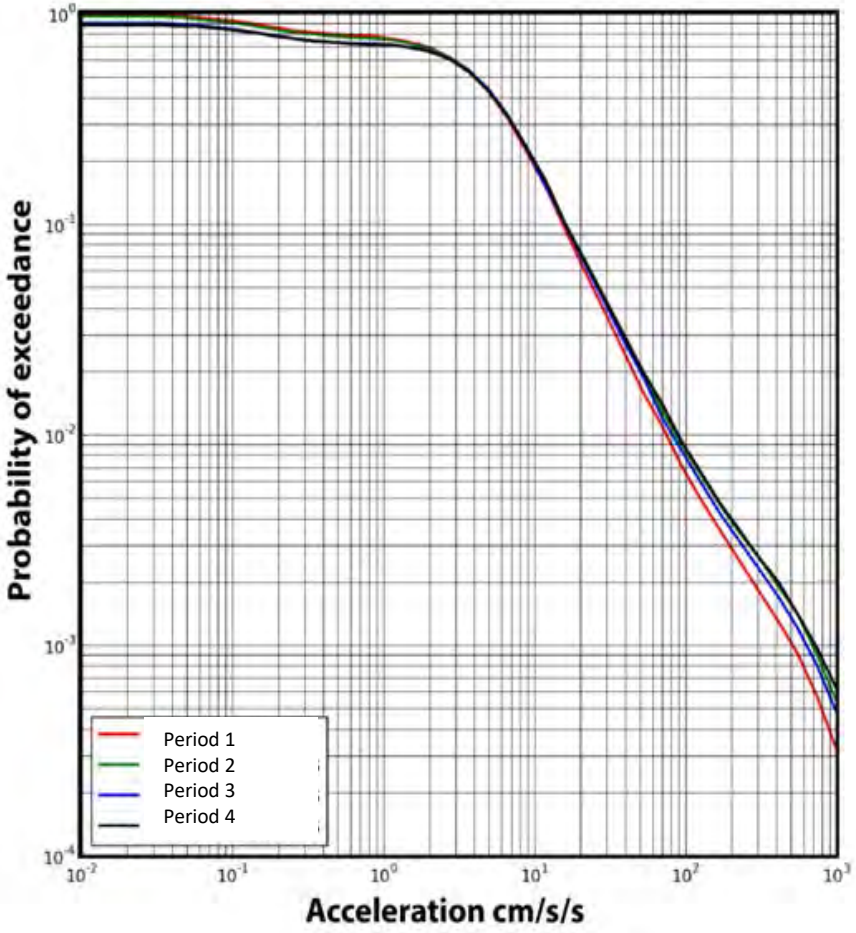
Probabilistic Seismic Risk Assessment Tool (RiskCat)

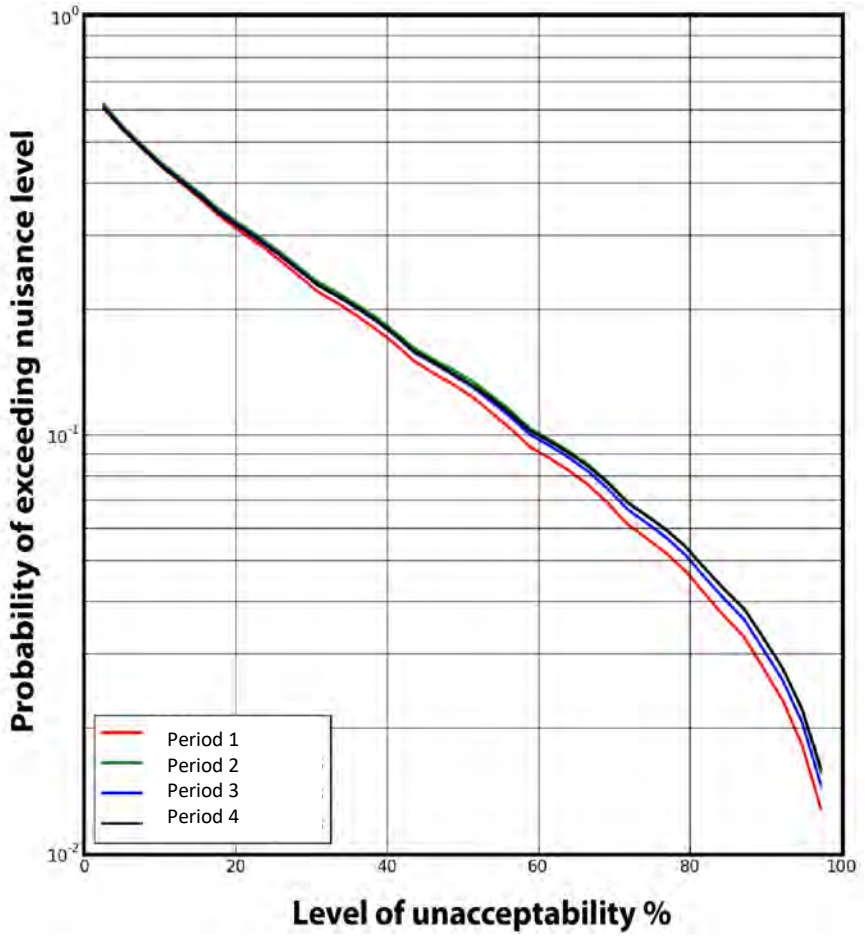
PSRA Workflow:



Reference: Jean Savy and Bill Foxall (2018) RiskCAT User's Manual.

Probabilistic Seismic Risk Assessment Tool (RiskCat)

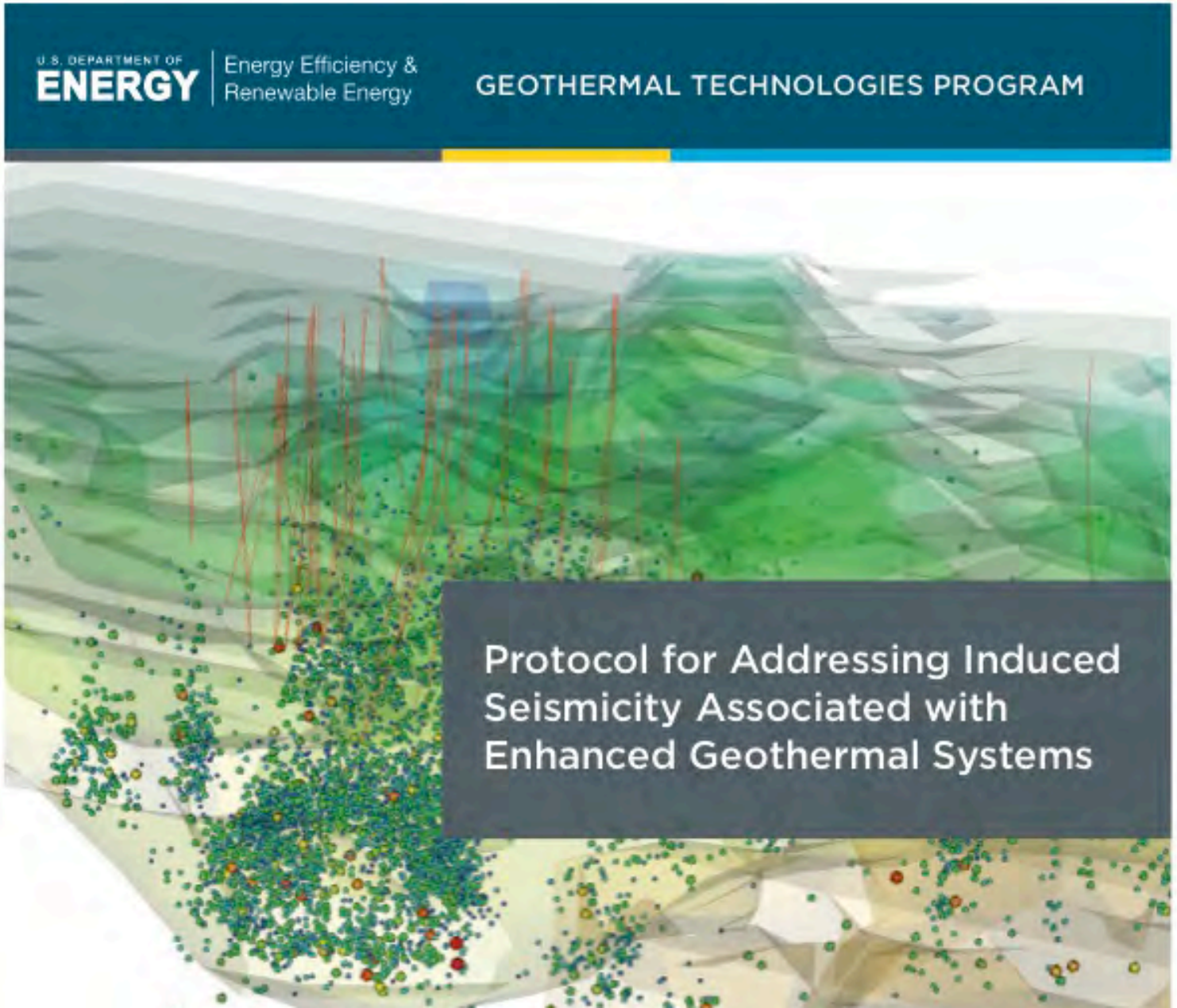




- Tool complete and undergoing internal testing
- Will be beta-released Fall 2018
- Targeting seismic risk community, rather than a general audience

Reference: Jean Savy and Bill Foxall (2018) RiskCAT User's Manual.

Carbon Storage Seismicity Protocol: Planned Effort



- **Starting Point:** GTO Geothermal Seismicity Protocol (2012).
- **Goal:** Develop best-practices guidelines relevant for carbon storage

Reference: E. Majer et al (2012).

Carbon Storage Seismicity Protocol: Planned Effort

GTO Seismicity Protocol: Primary Steps

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.

- **FY18-19 Plan**:
  - Work with original GTO authors to "update" protocol.
- **Three key components:**
  - Update with progress since 2012
  - Strengthen risk analysis components (Steps 5-7) using NRAP insights
  - Ensure relevance for carbon storage operations / scale

Reference: E. Majer et al (2012).

Lessons Learned

- **We need to do a better job integrating our risk assessment methods into existing industry practice**
  - Essential for engagement and tech transfer
  - Protocol and Recommended Practices should help here

- **We have a diverse set of stakeholders, with different but equally important needs**
  - Operators:
    - Writing permits
    - Day-to-day site management
  - Regulatory authority
    - Evaluating permits
    - Regional-scale management
  - Public
    - Context for evaluating risks and benefits

Synergy Opportunities

- **Always looking for partners with microseismic data**
  - CO_2 is most relevant, but other injection operations can be good analogs

- **Always valuable to hear about specific needs from stakeholders**
  - Allows us to maximize technical impact

- **NRAP is focused on a narrow component (risk assessment) of a very large problem (seismicity)**
  - Eager to engage with broader community, particular other DOE-funded initiatives

Program Goal No. 4

- Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.

Benefit Statement

- An understanding of induced seismicity is essential for effective risk management of storage sites.
- This project seeks to develop:
  - An open toolkit to support seismic characterization and management.
  - Support best-practices to minimize risk while supporting the growth of the CO_2 storage industry

Phase II Workscope

- **Task 3.1 – Real-time Hazard Forecasting**
  - **Focus:** Improve Short-Term Seismic Forecasting (STSF) tool by testing new forecasting methods and improving tool usability.
- **Task 3.2 – Active Seismicity Management**
  - **Focus:** Study effectiveness of different techniques (e.g. pressure control) for managing seismicity at problematic sites.
- **Task 3.3 – Probabilistic Seismic Risk Assessment**
  - **Focus:** Transition NRAP workflow to a practical industrial workflow by partnering with stakeholders in the seismic risk consulting world.
- **Task 3.4 – Fault Leakage (Deferred to FY19+)**
  - **Focus:** Targeted monitoring and active mitigation of fault leakage (through, e.g., hydraulic barriers).
- **Task 3.5 – Seismicity Management Protocal (Prioritized for FY18-FY19)**
  - **Focus:** Best-practices protocol for CO_2 seismicity management, supported by a suite of tools to help stakeholders implement a practical workflow.