Refining Principal Stress Measurements in Reservoir Underburden in Regions of Induced Seismicity through Seismological Tools, Laboratory Experiments, and Theory

Project Number: FE0031687

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National Energy Technology Laboratory

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Presentation Outline

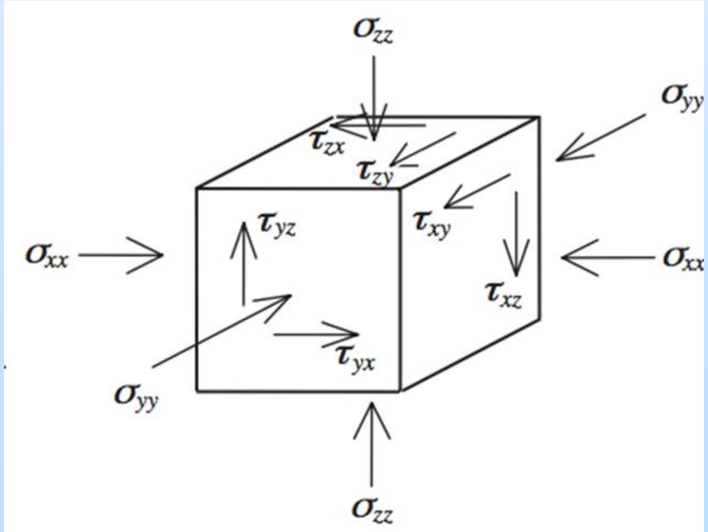
- Technical Status
- Accomplishments to Date
- Project Summary
- Appendix
  - Benefit to the Program
  - Project Overview: Goals and Objectives
  - Organizational chart
  - Gantt Chart
  - Bibliography

Motivation

- Successful storage of large volumes of CO_2 in the subsurface requires improved understanding of the state-of-stress in the subsurface in order to mitigate the hazards associated with storage integrity and induced seismicity.
- Significant advancements have been made in carbon storage technology. However, key gaps in experience and knowledge remain. One of these key gaps is the lack of certainty in predicting the geomechanical impacts of pressure migration due to injection into a storage complex.

Project Goal

- Develop methodologies to measure the in-situ principal stress, at and below reservoir depths (1.5-6 km), through use of multiple independent, but complementary **seismic methods**, **laboratory verification**, and development of **theoretical frameworks**



Hudson et al., (2003)

Methodology

Seismic Analysis
Task 2

Seismic processing tools (VSM & SWS) applied to seismicity catalogs (from matched filter techniques)

Laboratory Testing
Task 3

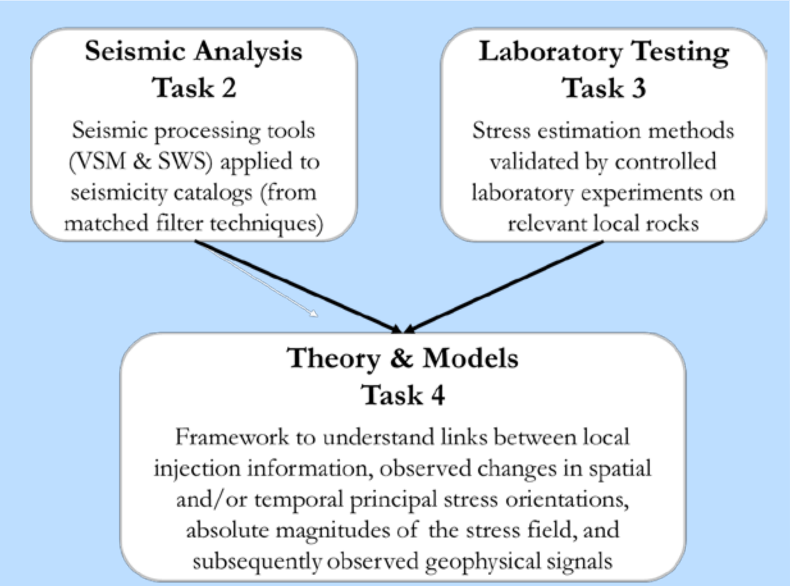
Stress estimation methods validated by controlled laboratory experiments on relevant local rocks

Theory & Models
Task 4

Framework to understand links between local injection information, observed changes in spatial and/or temporal principal stress orientations, absolute magnitudes of the stress field, and subsequently observed geophysical signals

Methodology (cont'd)

- Development will be carried on in three stages:
  - Method development - Kansas
  - Method refinement - Oklahoma
  - Method validation - California



Seismic Analysis (Task 2) – Focus of current work

Evaluate the spatial and temporal rotation of the stress field

1. **Matched Filter Catalog Development**: reduces M_c and increases number of events in catalog
2. **Focal Mechanism and Moment Tensor Analysis**: provides kinematic estimates for fault slip; FM inversion recovers stress tensor components

Seismic Interferometry: subsurface properties

3. **Ambient Noise Tomography** (ANC): uses the energy of the ambient background field

Seismic Analysis (Task 2) – Focus of current work – (cont'd)

Seismic Interferometry: subsurface properties

4. **Virtual Seismometer** (VSM): focuses on the source region

5. **Shear Wave Splitting** (SWS): estimates of the change in crack orientation and aperture due to injection

Laboratory Testing (Validation of results from seismic observations) - Task 3

Task 3.1: Characterization of Mid-Continent Basement Rocks

- Measure **seismic anisotropy** in **laboratory** samples
- Retrieve **Vp/Vs measurements** for basement rocks.
- Use thin sections to determine microstructural controls on anisotropy.

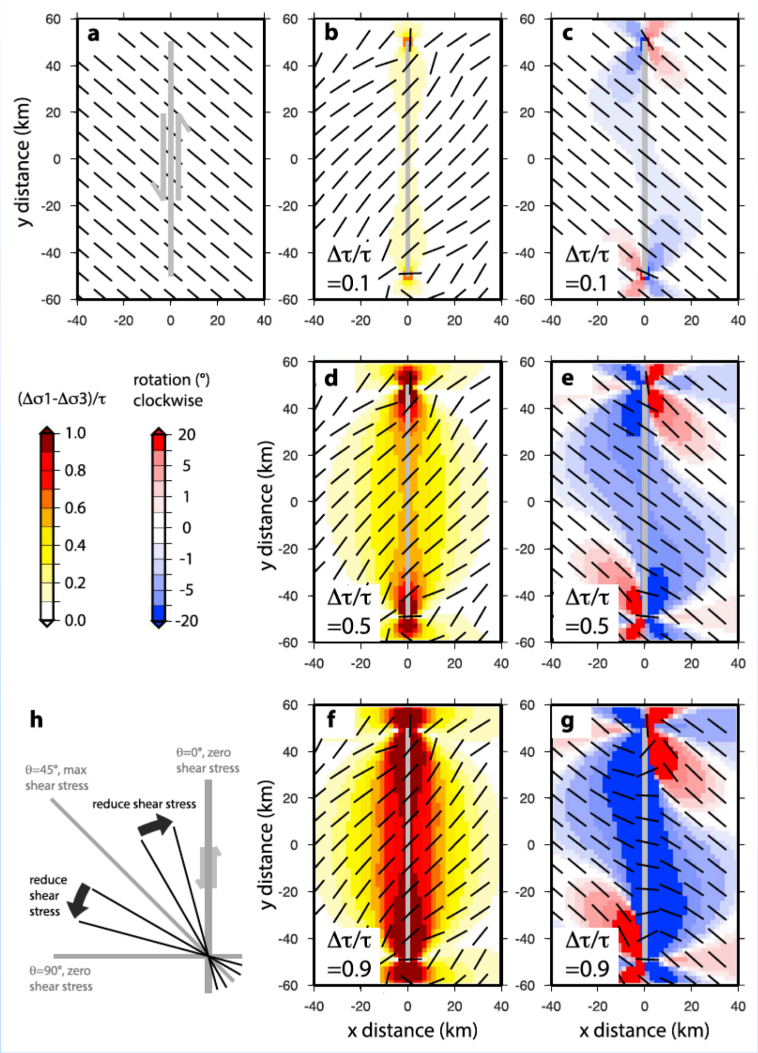
Task 3.2: Synthesis of Petrophysical Observations

- Illuminate regional **basement fracture characteristics** via 3D seismic interpretation.

Theory and Modeling - Task 4 (Complete stress tensor)

- Use results from Task 2 & 3, velocity models, focal mechanism, measured stress rotations, 4 (or 5) stress tensor components, to constrain 6^{th} component of stress tensor
  - 4.1 Geomechanical Modeling
  - 4.2 Theoretical Framework

Theoretical Framework (Complete stress tensor estimation)



Hardebeck and Okada, 2018

- Traditional focal mechanism inversion
  - 4 stress tensor components
  - 5 if coseismic stress changes are used
    - This relies on oversimplified estimates of σ_{xx} and σ_{yy}
- Develop constitutive relationship that links seismic observations and pore-pressure changes to the components of the stress tensor

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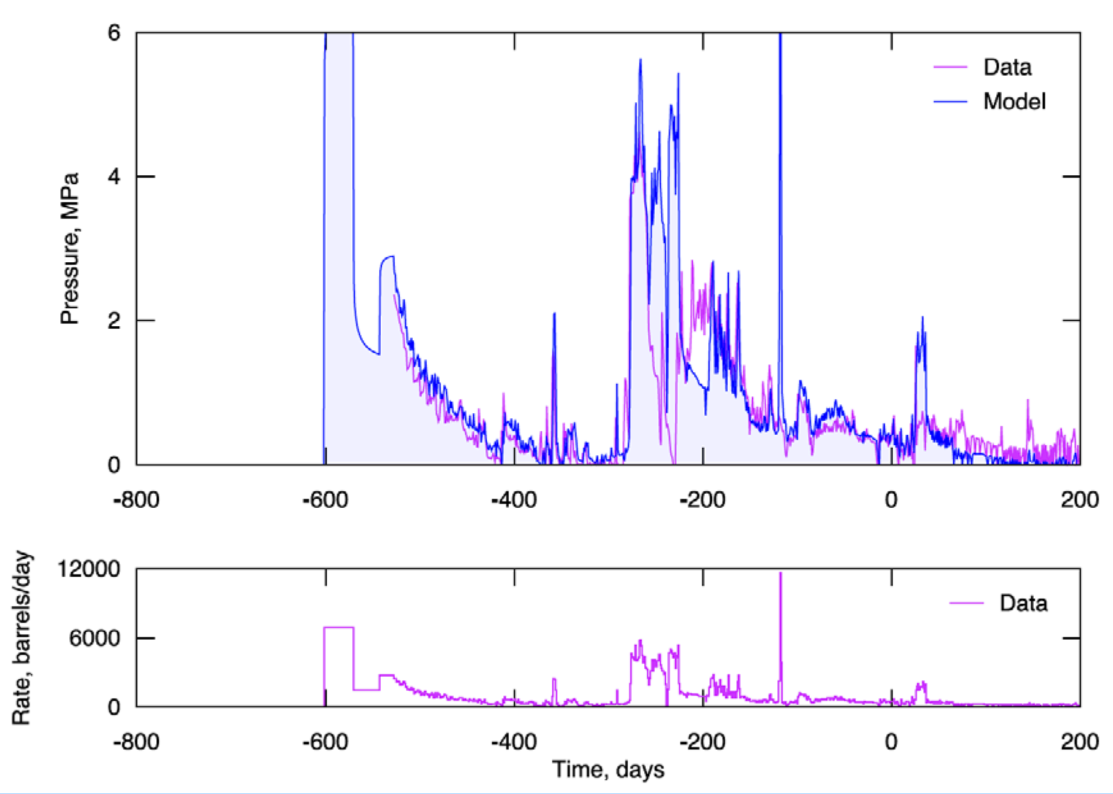
Theoretical Framework



Kroll et al., 2018

- Use injection/pressure data to constrain reservoir properties and compute pressure change
- **Replace** coseismic stress with pressure change
- Develop model relating observed stress rotation and pore-fluid pressure

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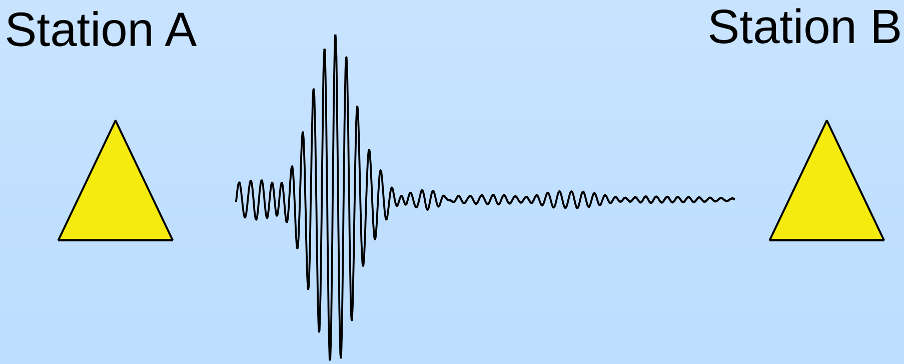
Accomplishments to Date

- Task 2: Seismic Analysis
  - Matched Filter Catalog Development
  - Focal Mechanism & Moment Tensor Analysis
    - Completed 1D, 2D, 3D, and 4D preliminary stress inversion for the Kansas matched-filter dataset using MSATSI. These will be used as a baseline with which to measure relative rotations against, using the VSM results.
  - Ambient Noise Tomography
  - Virtual Seismometer
  - Shear Wave Splitting

Ambient noise correlation: enables sharp 3D imagery of the Earth.

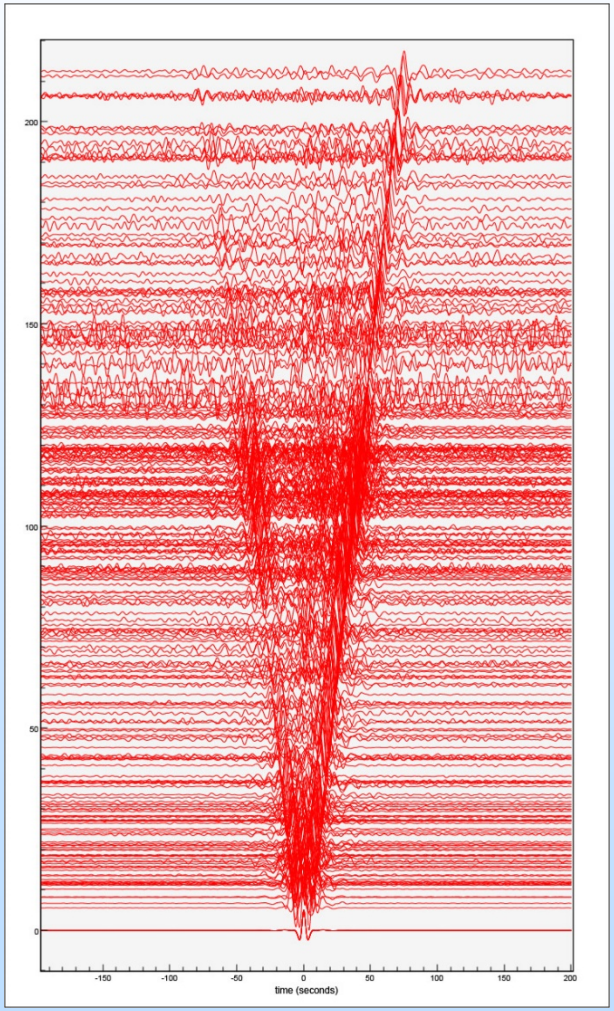
- Uses the energy of the background wavefield
- Completely passive
- Provides a simple estimate of the Green Function (GF)
- Once the signal emerges from the noise, the GF is very stable
- Even small variations in the GF are significant
- **Allows precise imaging and 4D monitoring**



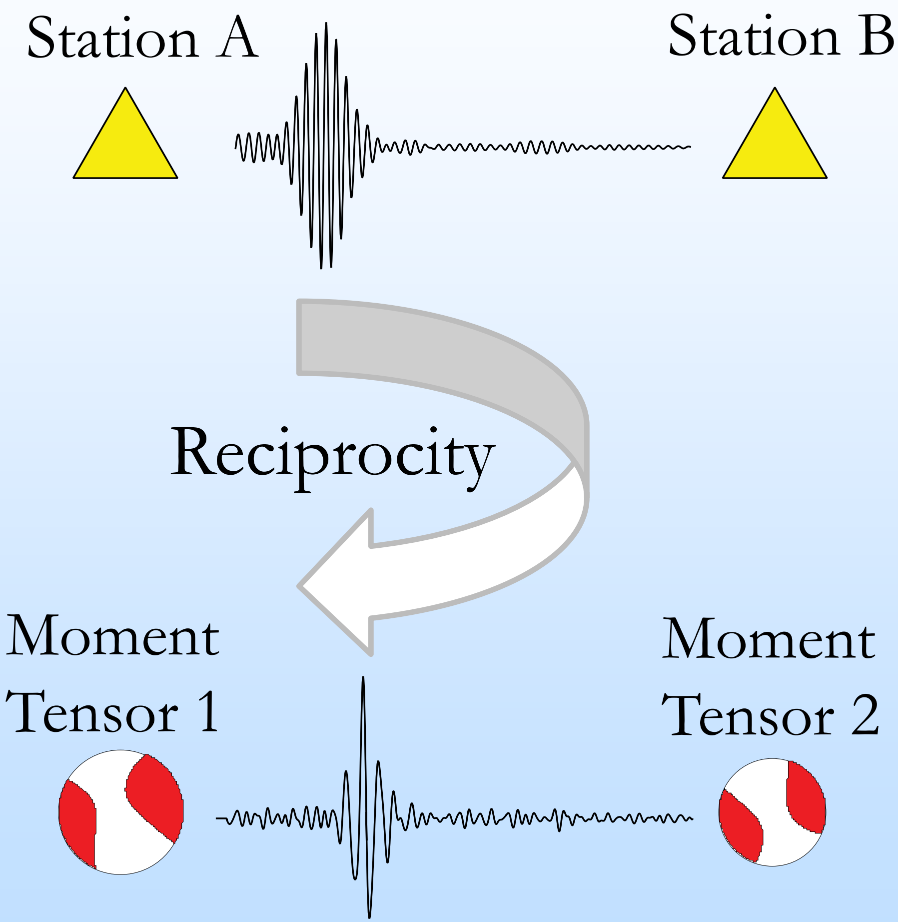
ANC Accomplishments to Date

- We have calculated over 1300 ANC waveforms for paths covering Southern Kansas and Northern Oklahoma
- Objective: Hight resolution 3D Velocity model

Kansas ANC waveforms



Virtual Seismometer (recovers relative moment tensor between events)



ANC

"virtual earthquake"

$CC = GF_{AB}$

- Perfect location
- Perfect timing
- Simple estimate of the GF.
- Focused on the region defined by the network

VSM

"virtual seismometer"

$CC = M_1 \ M_2 \ GF_{12}$

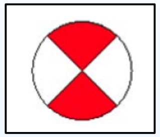
- Uncertain locations
- Uncertain origin times
- Complex GF
- Focused on the tectonically active region

Both methods: Ncorrelations = N*(N-1)/2

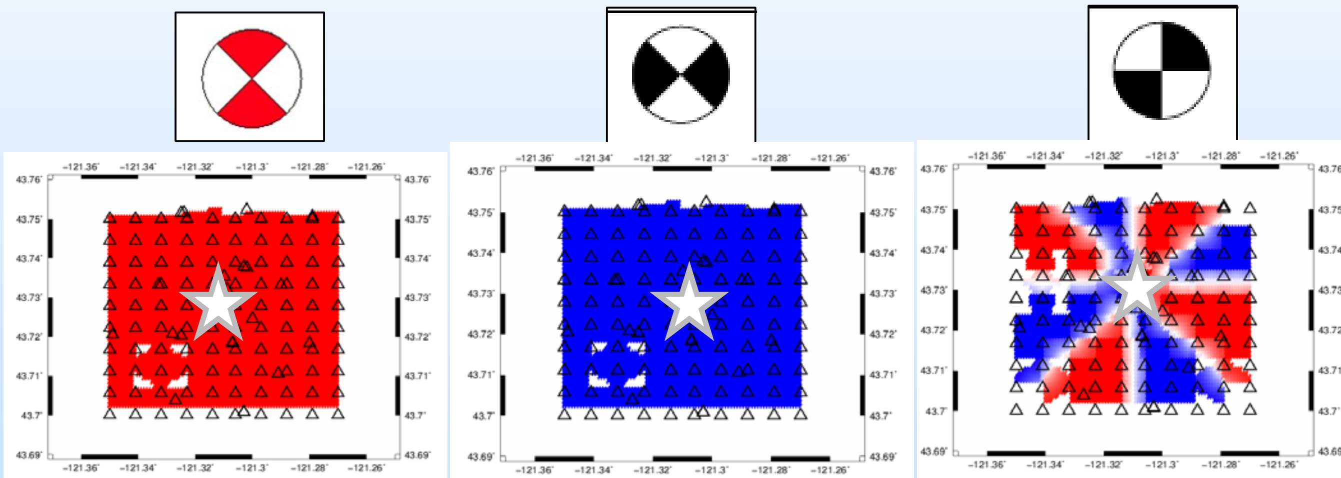
After Curtis et al., 2009

VSM detect changes in fault rupture

With a dense geophone network, VSM directly shows relative FM

Master event:  located  above a second event VS_i

VS_1 VS_2 VS_3



Surface views of the polarity of each cross correlated signal between 2 events, recorded at each geophone **= first order VSM**

The polarity maps offer different information

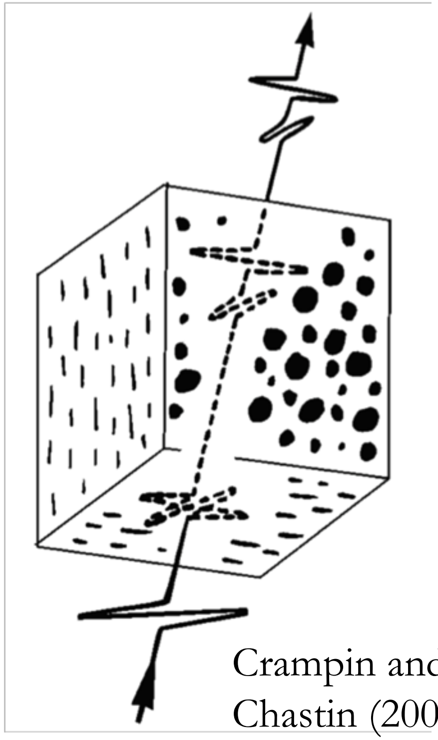
- All positive polarities = VS_1 , both events have the same FM, same type of rupture
- All negative polarities = VS_2 , opposite type of rupture
- More complex patter = VS_3, shows rotation of the focal plans, different type of rupture

VSM Accomplishments to Date

- Calculated > 1300 ANC waveforms and performed initial inversions for Vs, Vp and Q across Southern Kansas & Northern Oklahoma.
- Calculated > 20,000 VSM waveforms to measure Vs,Vp and Q in the tectonically active region in Kansas.
- Using localized VSM, preliminary results show changes in focal mechanisms, related to changes in fault activation, using 2016-2017 of public seismic data at stations in Kansas and Oklahoma (IRIS) and using the USGS catalog of the corresponding relocated events

Shear Wave Splitting Analysis (Estimates of the change in crack orientation & aperture due to injection)

- Anisotropy is due to:
  - Microcrack field aligned with local stress
  - Structural fabric near faults
  - Intrinsic material anisotropy
- Measure 'split' shear waves
  - Quasipolarized shear waves align parallel and perpendicular to local microcrack field



Crampin and Chastin (2003)

What can anisotropy measurements tell us?

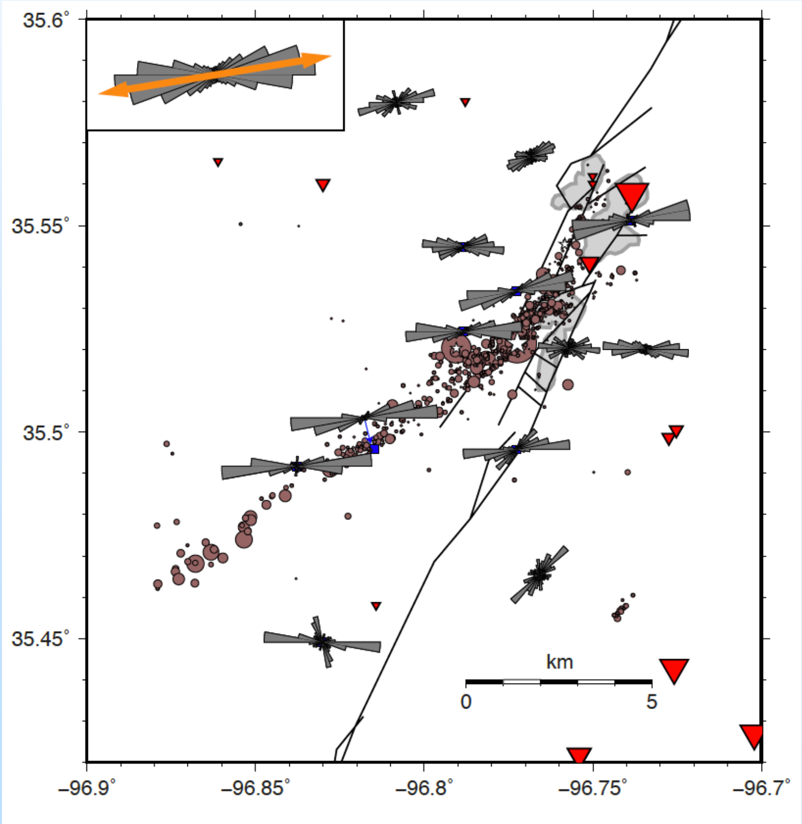
- Local rotations in stress field
- Locations of shear planes
- Temporal variability in strength or direction of anisotropy due to a local stress change

Shear Wave Splitting Analysis (Estimates of the change in crack orientation & aperture due to injection)

DOE funds to USGS are still pending completion of agreements. We show relevant work from a region in Oklahoma not proposed for the project.

2011 Prague earthquake

- Complex rupture across 3 fault planes could suggest variability in local stress field
- Dense temporary array data (similar to what will be used in Kansas analysis) recorded the aftershock sequence.
- Dominantly E-W fast directions observed on stations that matches previous estimates of the regional stress (N80E).

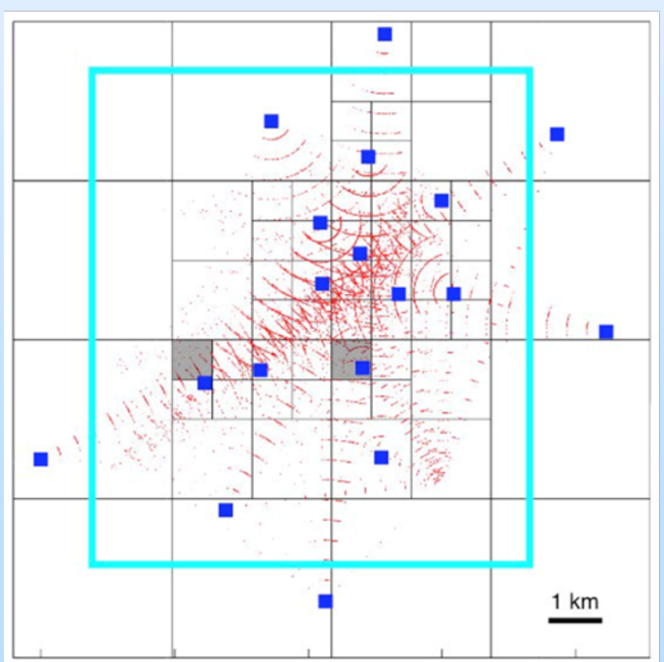


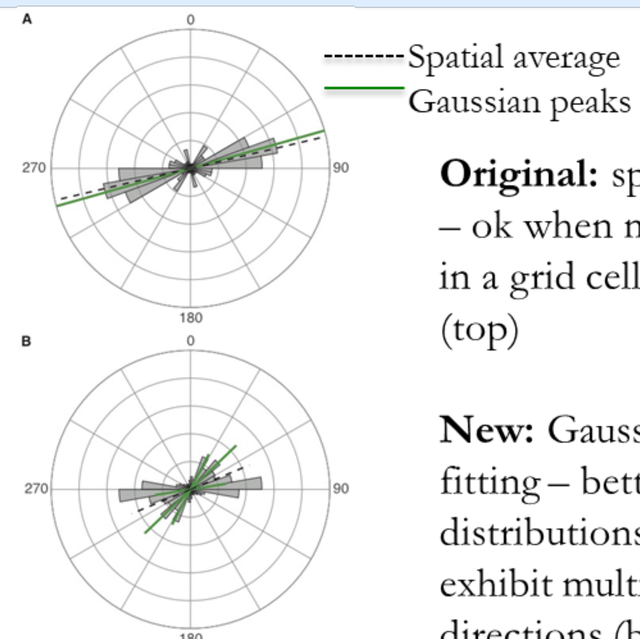
Shear Wave Splitting Analysis (Estimates of the change in crack orientation & aperture due to injection)

DOE funds to USGS are still pending completion of agreements. We show relevant work from a region in Oklahoma not proposed for the project.

Improved spatial resolution

- Analyze results on a quadtree grid
- Developed improved statistical measure of the dominant fast direction(s)





Original: spatial averaging – ok when measurements in a grid cell are consistent (top)

New: Gaussian peak fitting – better captures distributions in a cells that exhibit multiple fast directions (bottom)

SWS Accomplishments to Date

DOE funds to USGS are still pending completion of agreements. We show relevant work from a region in Oklahoma not proposed for the project.

- Development of workflow & algorithms which will allow for:
  - Improvement of spatial resolution
  - Analysis of results on a quadtree grid
  - Improved statistical measure of the dominant fast direction(s)

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Project Summary

- Preliminary results from seismic analysis task indicate result from Kansas data set are consistent with previously published work
- Preliminary analysis suggest that robust results may be obtained despite limited station coverage
- Lessons Learned: When there are multiple participating institutions contract negotiations could be lengthy and complex
- Next Steps:
  - Analysis of the spatial and temporal rotation of the stress field (BP2)
  - Method development (incorporating laboratory validations) (BP2)
  - Laboratory measurements in Kansas data set (BP2)

Appendix

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Benefit to the Program

- This proposal will assist DOE's Carbon Storage program and industry to **address key gaps in experience and knowledge in Carbon Storage Technologies such as the lack of certainty in predicting the geomechanical impacts of pressure migration due to injection into a storage complex**
  - To be able to predict the geomechanical impact of commercial scale carbon storage in the subsurface, understanding of the in-situ state of stress is essential. The work proposed here will develop, test, and refine a set of diagnostic tools for determining the in-situ stress state which will reduced uncertainty at and below reservoir depths (>1.5 km), allowing for better predictions of the geomechanical impacts of pressure migration in a storage complex.
- Furthermore, it will assist with one of this FOA goals of developing tools to better measure and understand the in-situ stress state, **in particular the maximum principal stress in the deep subsurface**
  - The work proposed here will develop methodologies through use of multiple independent, but complementary seismic methods, laboratory verification, and development of theoretical frameworks to better measure and understand the in-situ state of stress, in particular the maximum horizontal stress.

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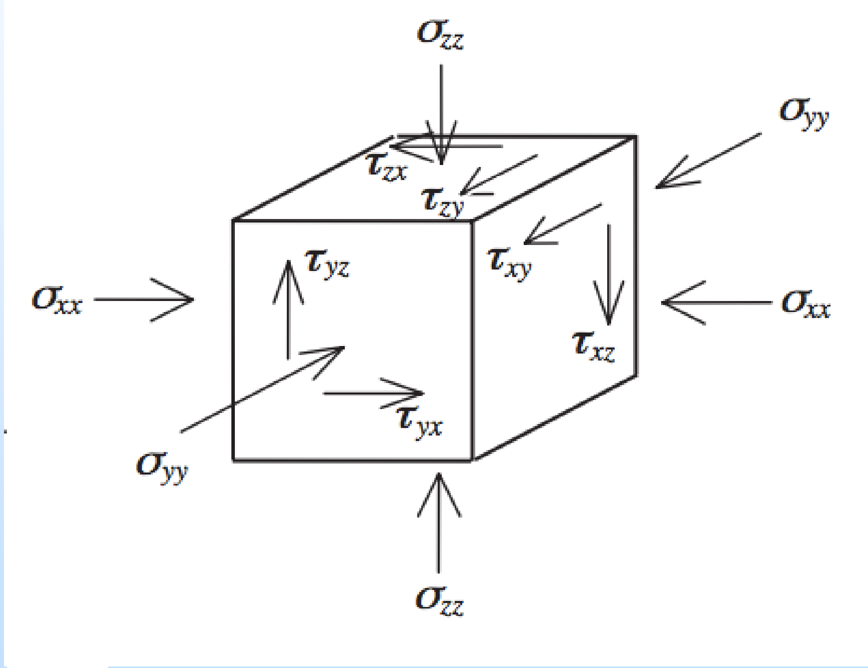
Project Overview:
Goals and Objectives

- Develop methodologies to measure the in-situ principal stress, at and below reservoir depths (1.5-6 km), through use of multiple independent, but complementary seismic methods, laboratory verification, and development of theoretical frameworks

Project Goals

- Evaluate the stress field including spatial and temporal rotation due to injection



Hudson et al., (2003)

- Non-invasive, inexpensive, full tensor, spatial and temporal rotations
- Seismic methods plus geomechanical modeling
  - Primarily sensitive to deviatoric component
  - Pore pressure to constrain isotropic component

Expected Outcomes

- Scale independent methodology/set of tools to measure the in-situ principal stress in the deep subsurface (>1.5 km) which will allow for monitoring principal stresses in the underburden for carbon storage projects (as wells as waste water disposal, etc.).
- Additionally, expected outcomes include:
  - Robust microseismicity catalogs
  - High-resolution 3D seismic velocity models
  - Catalogs of relative and full moment tensors
  - Fast direction & delay time measurements from SWS
  - Stress orientations over a range of spatial scales for the field validation sites
  - Stress magnitudes derived from modeling studies

Decision Point

Task No.	Milestone Description
1.1	A: Updated Project Management Plan
	B: Project Kickoff Meeting with DOE
	C. Updated Technology Maturation Plan
	D. Updated Data Management Plan
2.1	E. Kansas Data Analysis
	G. Synthesize Seismic Methods
2.2	I. Refined Method applied to Oklahoma
2.3	K: Refined Method applied to California

Decision Point	Date	Success Criteria
Conduct review with DOE of progress to date and decide if any rescoping would be necessary	8/31/20	• Demonstrate results from ANT, VSM and SWS methods to Kansas microseismicity catalog &3D model and moment tensor elements calculation in combination with Geomechanical Modeling

Risk Matrix

- For this proposal, the highest risks are related to cutting edge technical tasks as well as data quality
  - Task 4.2 Stress magnitude estimation includes
    - Highest risk → open research question
    - Mitigation: using seismic inversion methods to estimate as many possible stress tensor components and constrain the remaining components with geomechanical models and laboratory analysis
  - Sufficient resolution of data might condition confidence on results
    - Mitigation options in cases where publicly available data resolution might not be sufficient include seeking proprietary data from Oil and Gas operators or relocating some of the study areas might be considered

Organization Chart

EPRI
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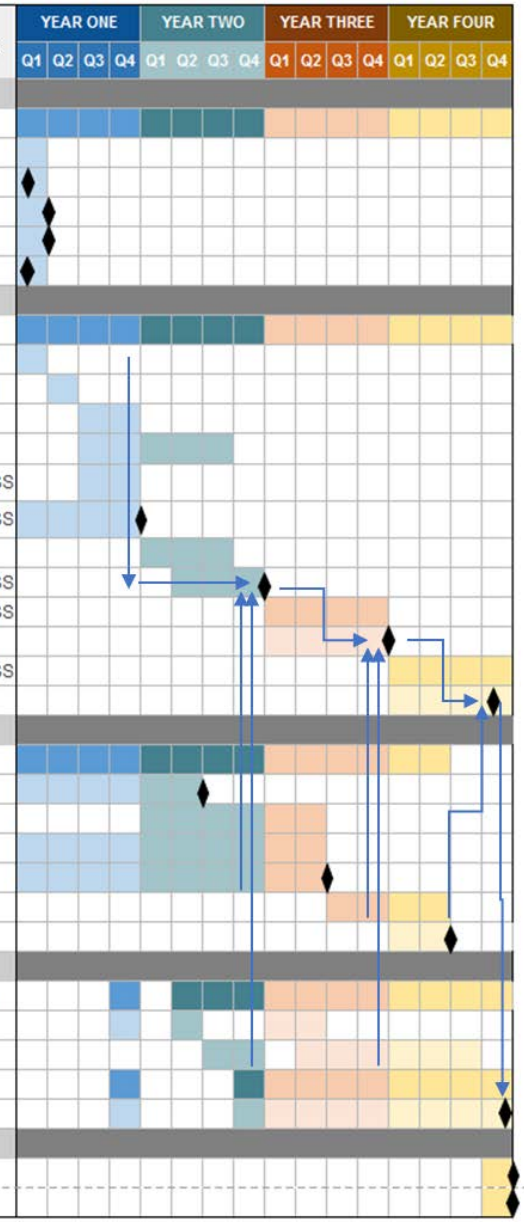
Gantt Chart

Task Number	TASK TITLE	ASSIGNED RESOURCES
1.0	**Project Management and Planning**	
1.1	Project Management and Planning	EPRI
	Sub-recipient contracting	
	Milestone A: Updated PMP	
	Milestone B: Project Kickoff Meeting with DOE	
	Milestone C: Updated TMP	
	Milestone D: Updated DMP (if requested)	
2.0	**Seismic Analysis**	
2.1	**Method Development - Kansas**	
	Catalog Development	USGS/OU
	Focal Mechanism and Moment Tensor Analysis	OU/USGS
	Ambient Noise Tomography	LLNL
	Virtual Seismometer	LLNL
	Regional Shear Wave Splitting	LLNL/OU/USGS
	Milestone E: Kansas Data Analysis	LLNL/OU/USGS
	Local Shear Wave Splitting	USGS
	Milestone F: Synthesize Seismic Methods	LLNL/OU/USGS
2.2	**Method Refinement - Oklahoma**	LLNL/OU/USGS
	Milestone I: Refined Method applied to Oklahoma	
2.3	**Method Application - California**	LLNL/OU/USGS
	Milestone K: Refined Method applied to California	
3.0	**Laboratory Testing**	
3.1	**Characterization of Mid-Continent Basement Rocks**	OU
	Milestone F: Single-Direction Sonic Characterization of Mid-Cont. Basement	
	3D Orthogonal Sonic Characterization of Mid-Cont. Basement	OU
	Microstructural Characterization of Microfractures in Exp. Samples	OU
	Milestone H: 3D Orthogonal Sonic and Michrostructural Analysis	
3.2	**Synthesis of Petrophysical Observations**	OU
	Milestone J: Synthesis of Petrophysical Observations	
4.0	**Theory and Models**	
4.1	**Geomechanical Modeling**	EPRI/LLNL
	Building Geomechanical Model	
	Hydro-mechanical modeling	
4.1	**Theoretical Framework**	ALL
	Milestone L: Integrated Theoretical Framework	
5.0	**Data Processing and Reporting**	
5.1	**Data to Energy Data eXchange (EDX)**	ALL
5.2	**Final Reporting (Prep. & Submittal)**	ALL



Bibliography

- Submitted Abstract to AGU Fall Meeting 2019:
  - Chiaramonte, L., Kroll, K.A., Cochran, E.S., Matzel, E., Morency, C., Skoumal, R.J., McPhillips, D., Walter, J.I., Carpenter, B.M, Ghassemi, A., Trautz, R., White, J.A., and Esposito, R. *submitted*. Refined Principal Stress Estimates for Induced Seismicity in Southern Kansas Based on Seismological Tools and Laboratory Experiments. ***Submitted*** to AGU Fall Meeting, 2019

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