Refined Principal Stress Estimates from Induced Seismicity in Southern Kansas and Oklahoma Based on Seismological Tools and Laboratory Experiments

Project Number FE0031687

Laura Chiaramonte, PI

EPRI

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management Project Review Meeting

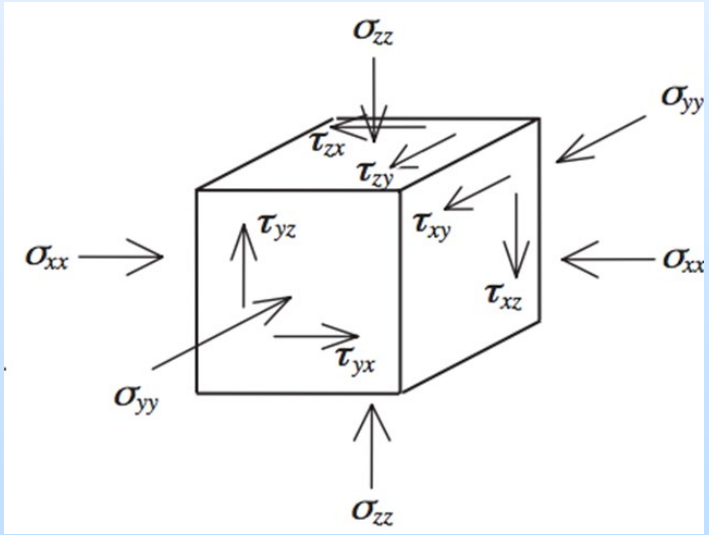
August 15 - 19, 2022

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.

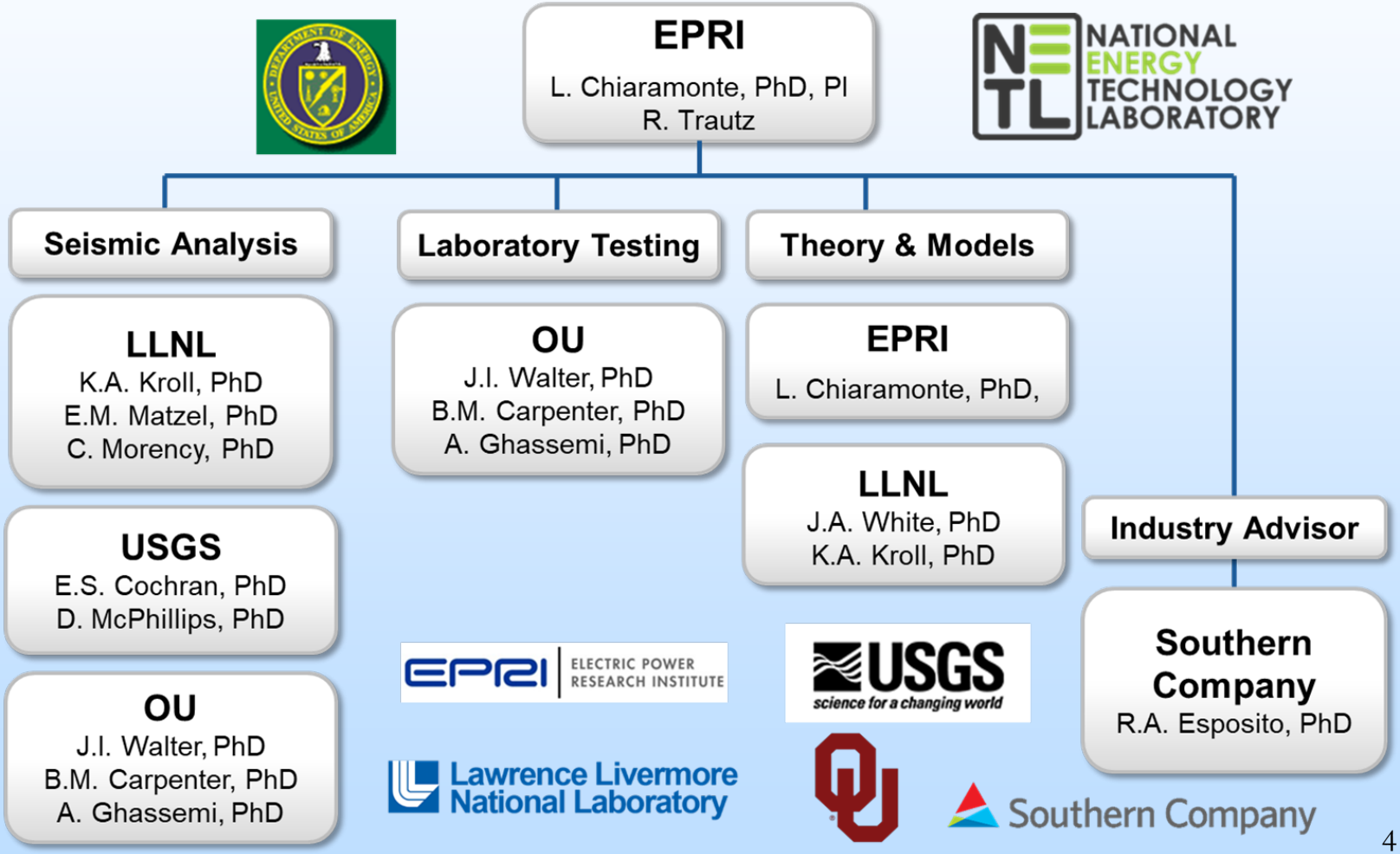
Project Goal

- Develop methodologies to constrain 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
- DOE & Southern Co. funded 4-year project
  - $2 MM DOE & $500k cost-share
  - 2018-2022 (with 9 month no-cost extension)
  - Area of study: southern Kansas & northern Oklahoma – wastewater injection as proxy for CO_2

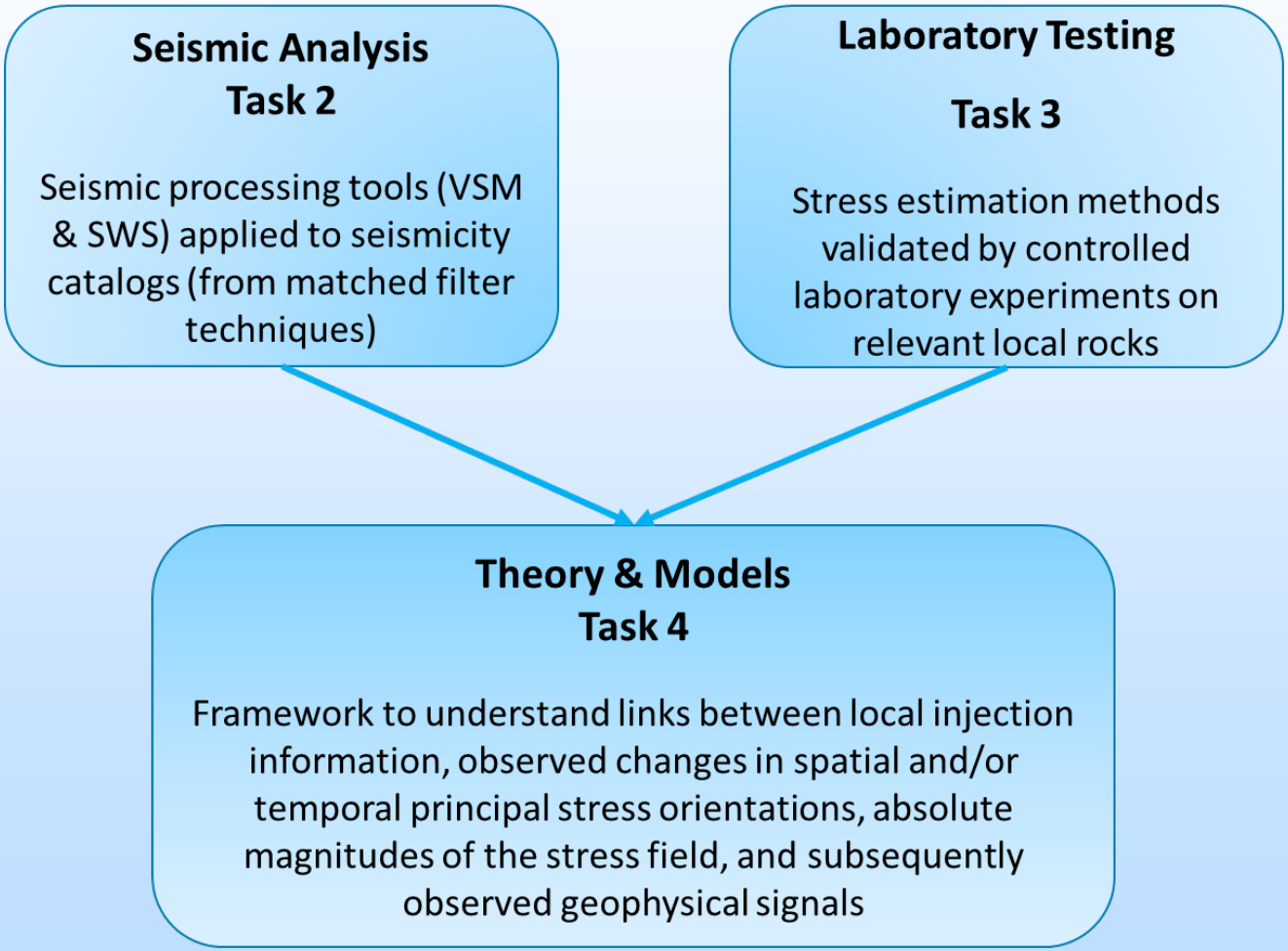


Hudson et al., (2003)

Project Participants



Methodology



Methodology (In-scope modification)

Development will be carried on in three stages:

- Method development - Kansas (BP1 & BP2)
- Method refinement – Oklahoma (BP3)
- Method validation – California (BP4)
  - In-scope modification to focus on VSM-MT uncertainty quantification and VSM-MT comparison to traditional methods

Google maps

Theoretical framework to constrain the in-situ stress & understand impact of injection in this region

- Based on minimum stress magnitudes, overburden stresses, relative stress ratios from FM inversion, estimates of Coulomb failure criterion for pre-injection seismicity, & fluid pressure change due to injection
- Quantify stress conditions along faults during injection & inform whether fault re-activation is due solely to increases in fluid pressure or rotations in the stress field
- The fundamental concept suggests that
  - standard deviation of range of re-activated fault orientations will be larger during injection compared to before injection if the triggering mechanism was caused by pressure changes
  - conversely, a shift in population mean, would indicate a rotation in the stress field, mostly likely associated with the disruption to the subsurface

Seismic Analysis (Task 2)

Evaluate the spatial and temporal rotation of the stress field

1. **Matched Filter Catalog Development**: reduces Mc 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

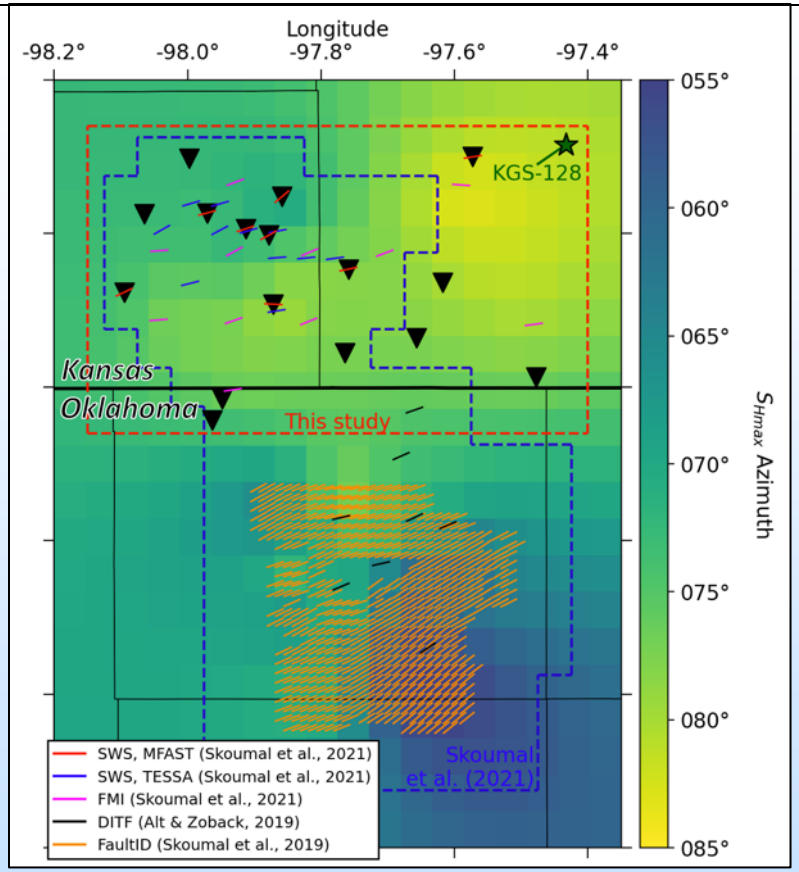
   Seismic Interferometry: subsurface properties
3. **Ambient Noise Tomography (ANC):** uses the energy of the ambient background field
4. **Virtual Seismometer (VSM)**: focuses on the source region
5. **Shear Wave Splitting (SWS):** estimates of the change in crack orientation and aperture due to injection

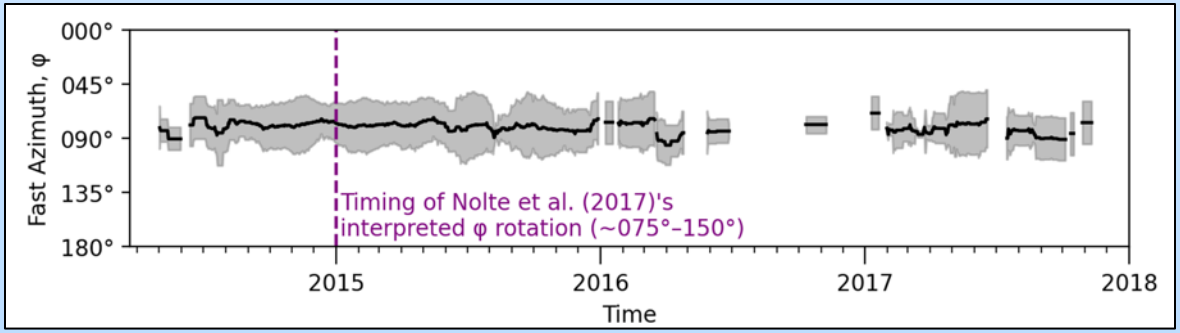
Accomplishments to Date Task 2: Seismic Analysis

– Task 2: Seismic Analysis
  - **Local spatiotemporal SWS & focal mechanism inversion analyses using microseismicity in Kansas (USGS) and expanded to OK**
  - Machine-learning/AI EQ catalog created for 2010-2021 in Jones area of central Oklahoma (OU)
  - Continuation of VSM analysis from Kansas to OK (LLNL)
  - Initial estimates of stress orientations and magnitudes conducted for Jones area based on SWS & focal mechanism inversion (USGS & LLNL)

Shear Wave Splitting: Southern Kansas

- We consider 5,831 relocated earthquakes with 45,022 manual S-wave phase arrivals during 2014-2017.
- φ results are consistent with DITFs and moment tensor inversions, with S_{Hmax} of ~N78ºE
- Using a stable local seismic network, we observe no significant, systematic temporal φ variations in southern Kansas, contrary to a previous study.

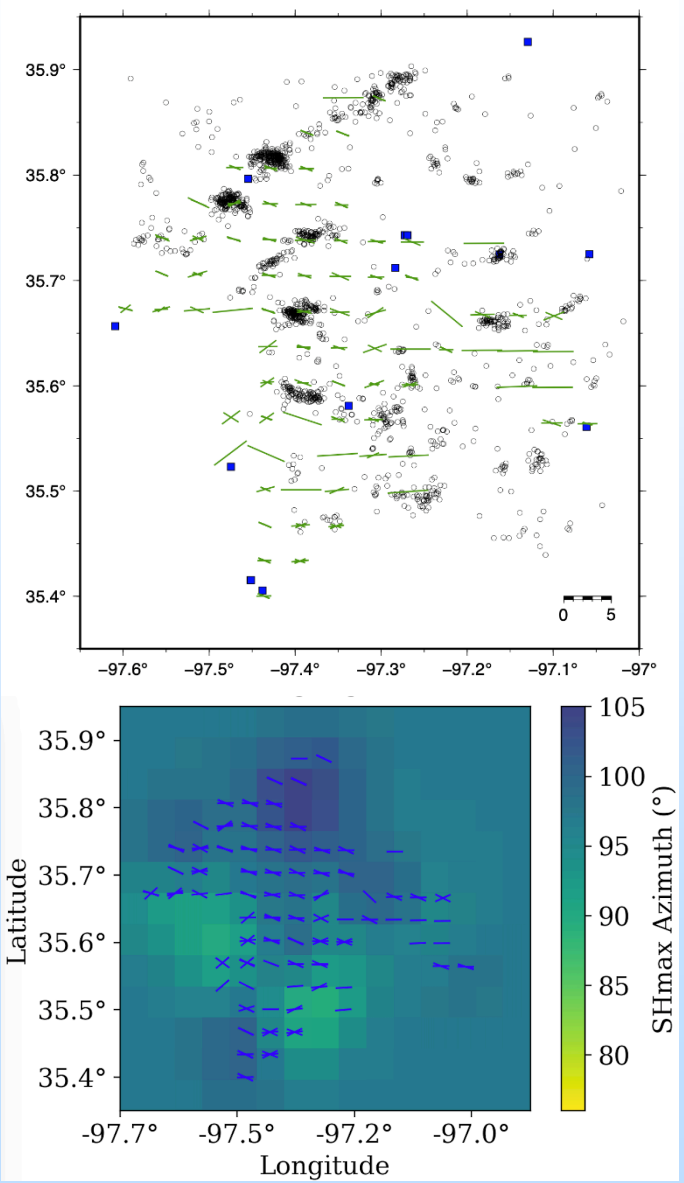




Publications:
Skoumal, R.J. & Cochran, E.S. (2021). Wastewater disposal has not significantly altered the regional stress state in southern Kansas, Seism. Res. Letts., 92, 3516-3525.
Skoumal, R.J., Cochran, E.S., Kroll, K.A., Rubinstein, J.L., and McPhillips, D. (2021). Characterizing stress orientations in southern Kansas, Bull. Seism. Soc. Am., 111, 1445-1454.

Shear Wave Splitting: Oklahoma

- Using a catalog of 5,508 earthquakes in Central Oklahoma, we made 2,090 high-quality SWS measurements.
- We found relatively stable fast directions in the study region that are oriented ~089° (nearly E-W).
- Gaussian regression using a circular variogram model considering the TESSA orientations creates a 2D stress map of the study region.

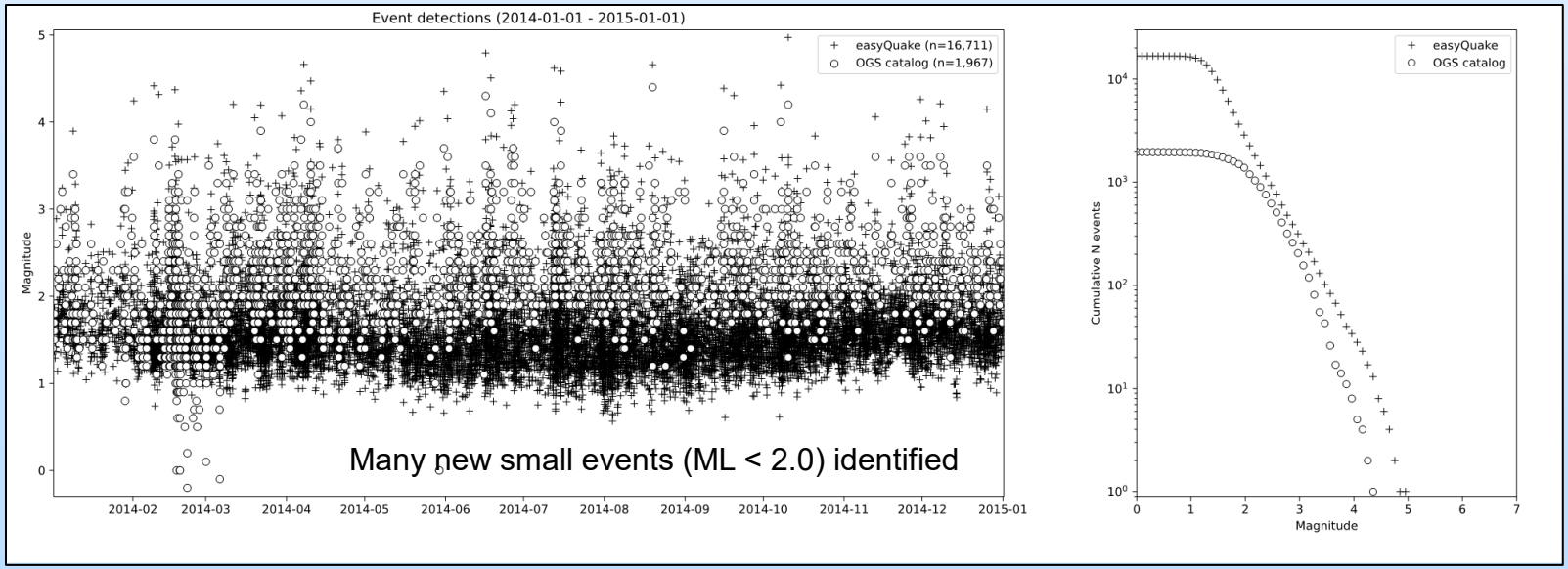


Accomplishments to Date Task 2: Seismic Analysis

– Task 2: Seismic Analysis
  - Local spatiotemporal SWS & focal mechanism inversion analyses using microseismicity in Kansas (USGS) and expanded to OK
  - **Machine-learning/AI EQ catalog created for 2010-2021 in Jones area of central Oklahoma (OU)**
  - Continuation of VSM analysis from Kansas to OK (LLNL)
  - Initial estimates of stress orientations and magnitudes conducted for Jones area based on SWS & focal mechanism inversion (USGS & LLNL)

Machine-learning/AI to find smaller earthquakes

- Catalog created for 2010-2021 in Jones area of central Oklahoma
- Lowers magnitude of completeness by ~1 unit
- Focal mechanisms from OGS analyst-picked catalog events re-computed using HASH (Hardebeck and Shearer, 2002) results in 351 "A" and 1,663 "B" quality events
- ML catalog being utilized for SWS (USGS) and VSM (LLNL)

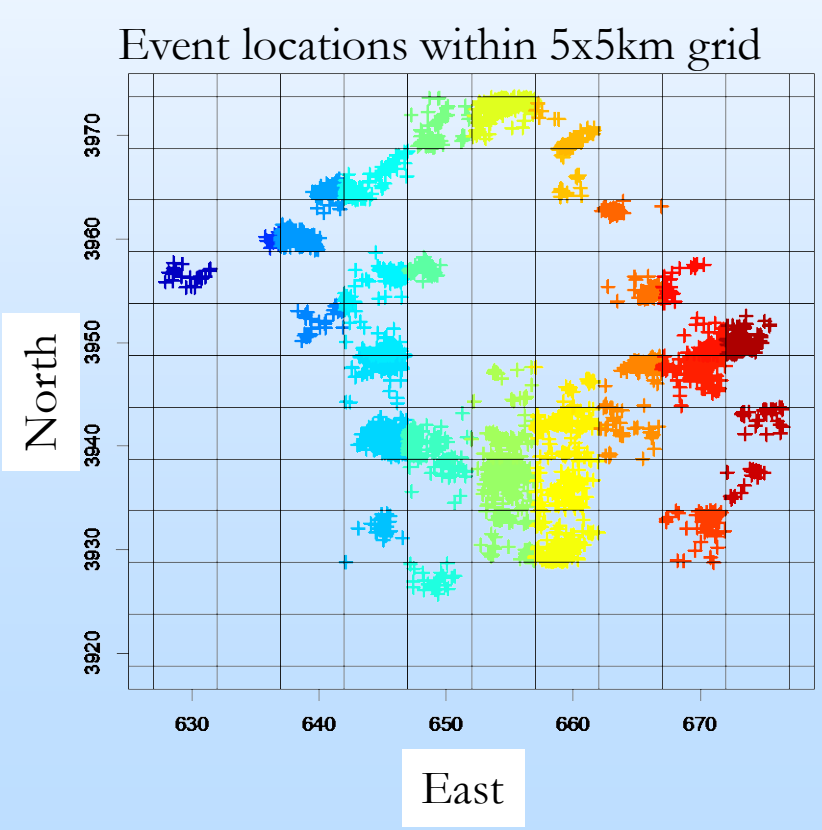


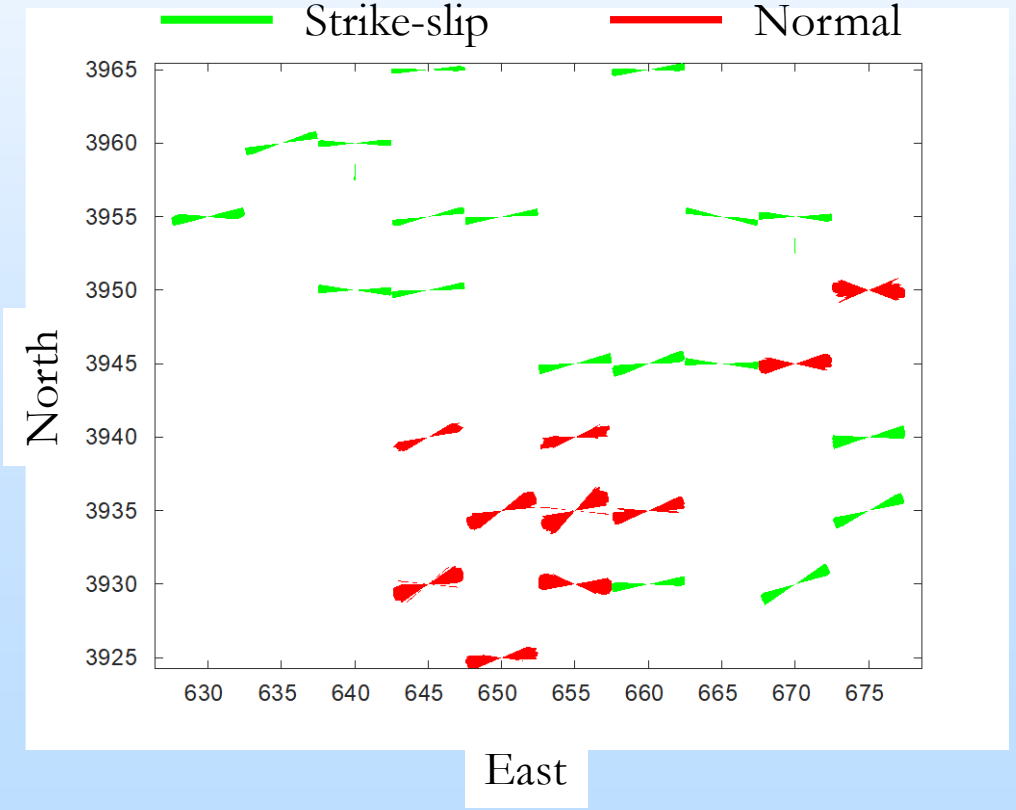
Accomplishments to Date Task 2: Seismic Analysis

– Task 2: Seismic Analysis
  - Local spatiotemporal SWS & focal mechanism inversion analyses using microseismicity in Kansas (USGS) and expanded to OK
  - Machine-learning/AI EQ catalog created for 2010-2021 in Jones area of central Oklahoma (OU)
  - **Initial estimates of stress orientations and magnitudes conducted for Jones area based on SWS & focal mechanism inversion (USGS & LLNL)**
  - **Continuation of VSM analysis from Kansas to OK (LLNL)**

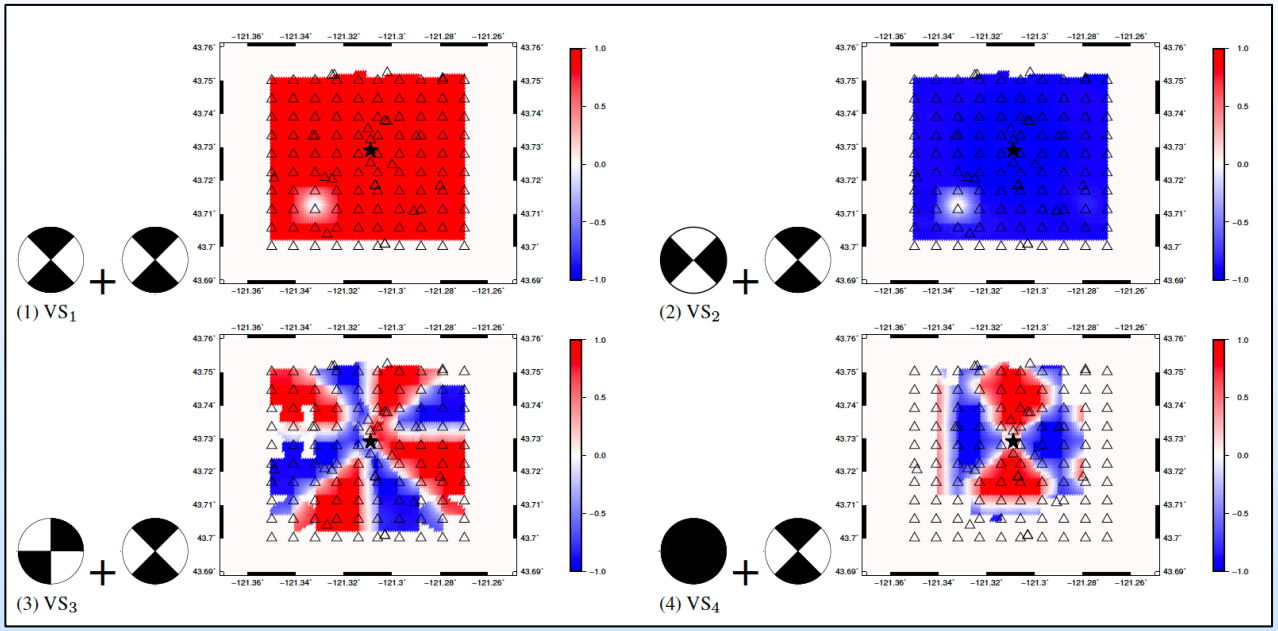
Stress Inversion for Jones, Oklahoma

- Stress inversion performed in MSATSI for 3299 events with HASH-FM solutions near Jones
- Magnitude range from M0.1 to M4.8
- HASH-FM: 85 quality "A", 436 quality "B", 403 quality "C", and 2375 quality "D"





The Virtual Seismometer calculation can identify the style of slip

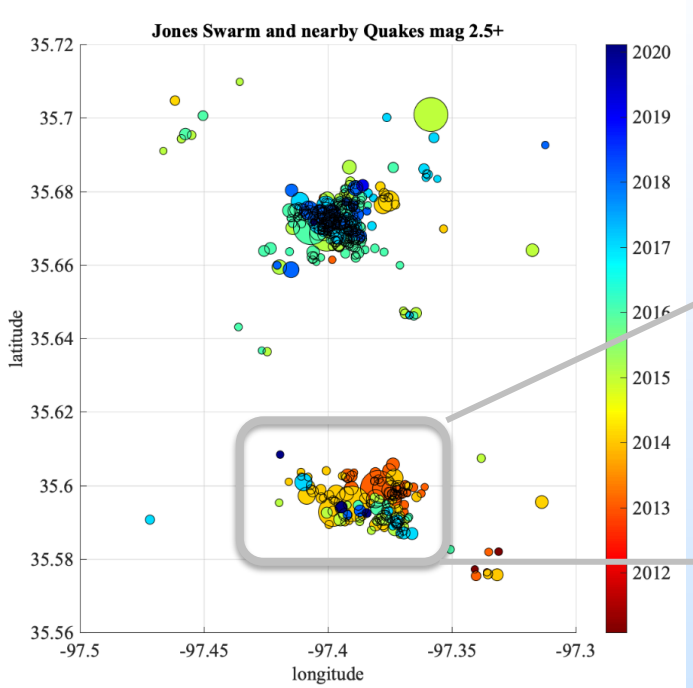


The amplitude of the VSM calculation as observed at different points highlights fault planes.

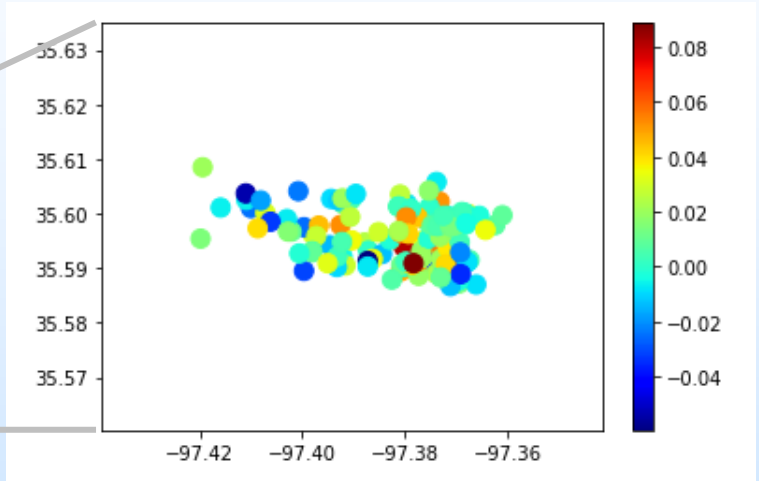
- We can quickly identify if the earthquakes are sliding along the same fault plane
- Or solve for the individual components if they are different

We have developed codes to measure focal mechanisms from VSM waveforms

Virtual seismometer method (VSM) for moment tensor inversion



similarity map (subset of 132 events)

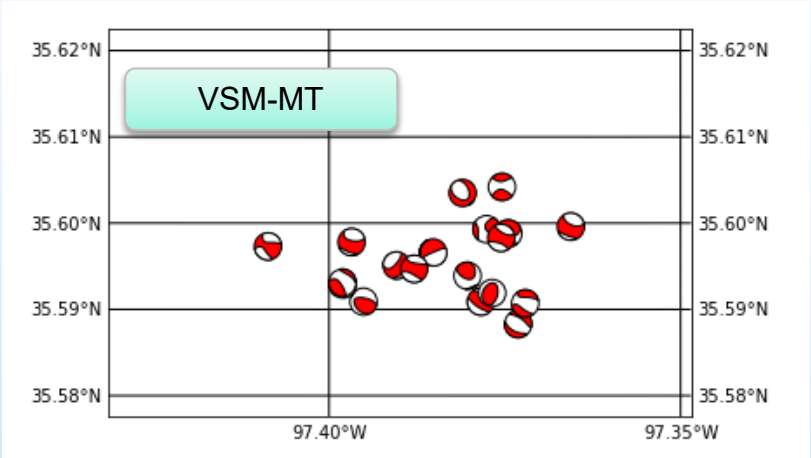


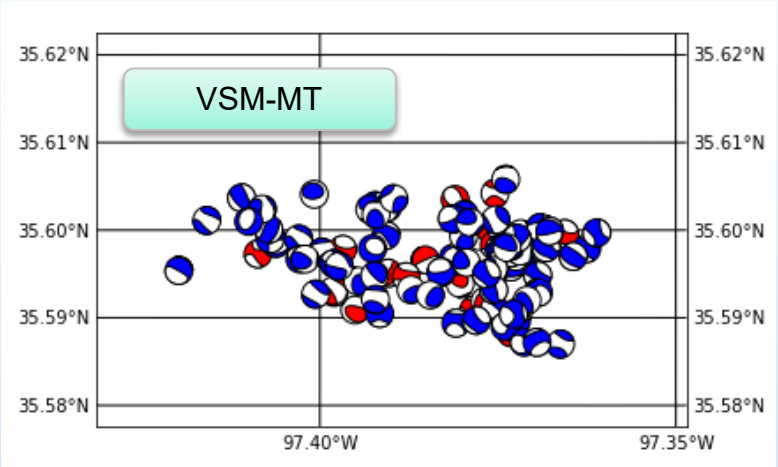
- Identified a subsection in the Oklahoma Jones sequence to perform VSM-based moment tensor (MT) inversion
- Selected 19 clustered events of quality A & B from a dense seismicity catalog using the HASH algorithm => 19 events reinverted for full MT solution and used a virtual seismometer network
- Using this virtual seismometer network of 19 events, we reinverted quality C & D events as well as events without a HASH solution, for full MT solution

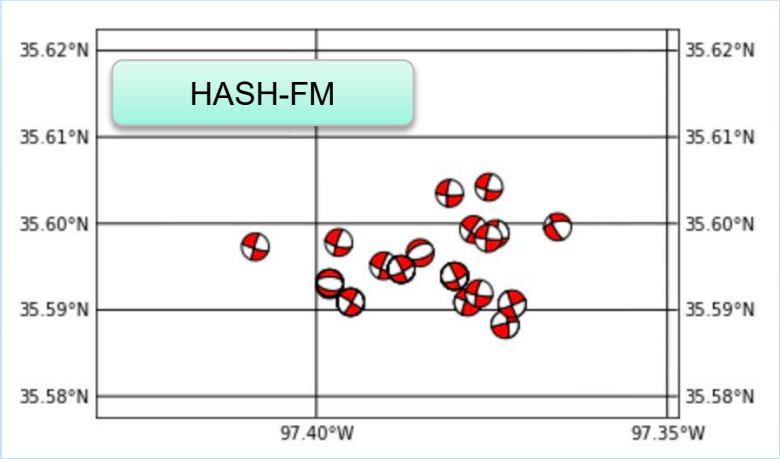
➢ *Can we get more information from VSM-based full MTs for stress orientation characterization?*

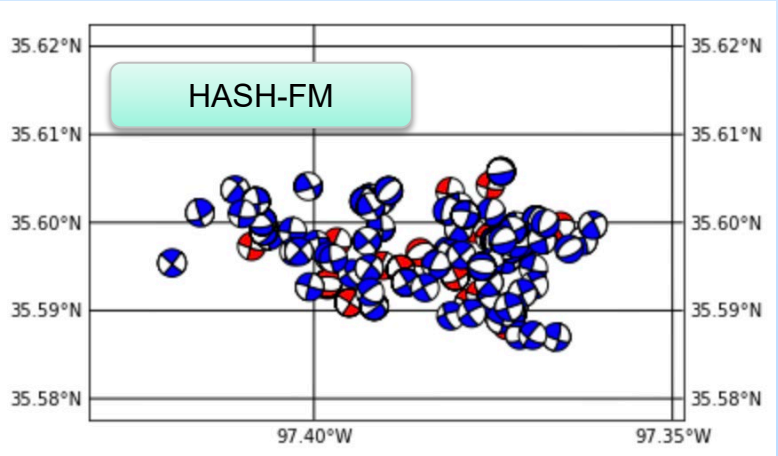
Virtual seismometer method (VSM) for moment tensor inversion (VSM-MT)

- Quality A & B events reinverted based on VSM
- **These 19 events are then used as a virtual seismometer network**
- Quality C & D events are reinverted using the virtual seismometer network



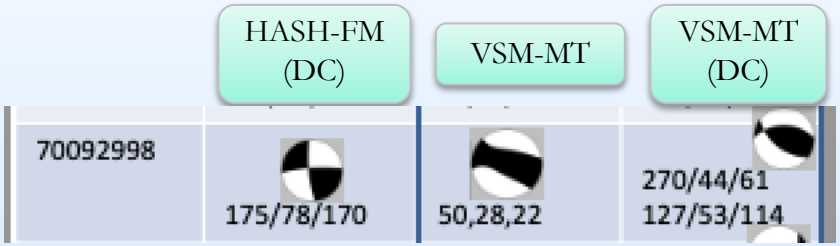


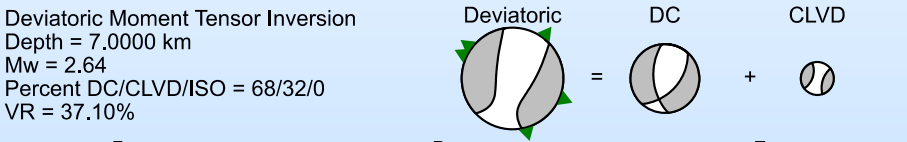




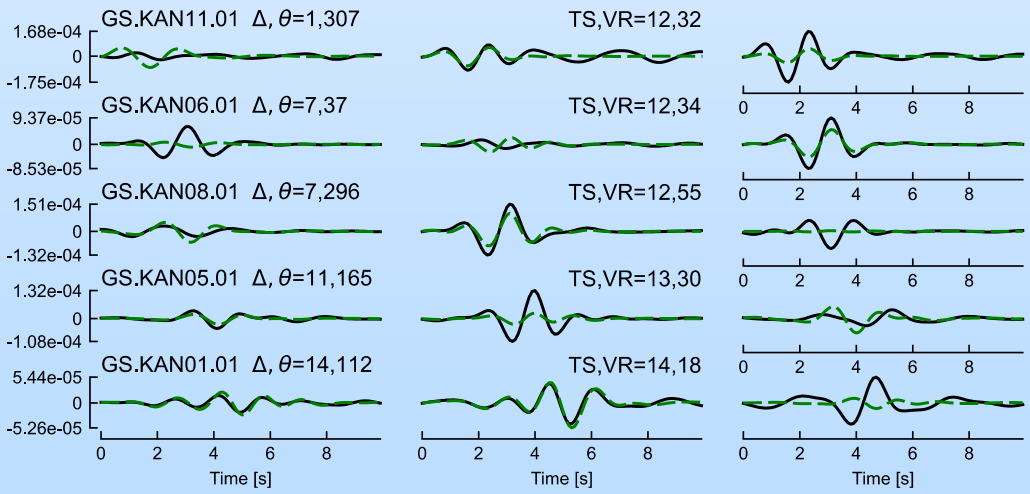
Moment tensor comparison

- M2.9 Kansas event compared across three methods:
  - HASH Focal Mechanisms from first motion
  - VSM-MT [moment tensor and double-couple (DC)]
  - Full Waveform Inversion [moment tensor and double-couple (DC)]





FWI-MT



Displacement

Observed

Synthetic

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**

Accomplishments to Date Task 3: Laboratory Testing

- Velocity anisotropy characterization in crystalline basement rocks of Oklahoma and Kansas.
- Observations were paired with thin-section characterization of fractures to demonstrate the effect of intrinsic anisotropy on basement rocks.
- Results show there is a considerable degree of velocity anisotropy in basement rocks. The basement rocks are shown to exhibit both pressure- and orientation-dependent velocity anisotropy regardless of the stress directions.
- Microstructural observations indicate crack anisotropy varies in the basement with depth, location, and rock type. Within certain lithologies, sufficient intrinsic anisotropy exists due to microcrack orientations to affect in-situ stresses determined by well log and geophysical measurements of velocity.
- The impact of intrinsic velocity anisotropy may be mitigated though with sufficient understanding of the regional basement lithology and comparison with other stress field determination methods.
- Current work focused on link measured lab anisotropy with SWS analysis.

Project Summary

- SWS & focal mechanism inversion are independent methods of inferring S_{Hmax} orientation & can be used in tandem to constrain stress orientations within/below reservoir depths.
- S_{Hmax} orientations in southern Kansas determined from SWS (~N78°E) and focal mechanism inversion (~N77°E) are consistent with previous regional estimates (e.g., Alt & Zoback, 2016) of an ENE orientation and provide greater spatiotemporal resolution. Preliminary S_{Hmax} orientations in central Oklahoma determined from SWS (N71°E) and focal mechanism inversion (N69°E) are also consistent.
- While our results do not indicate any significant spatiotemporal stress rotation, both SWS and focal mechanism inversion rely on spatially binning observations. The potential for local rotations (<10x10 km) may not be resolved.

Project Summary, cont

- Completed VSM-MT for Kansas and Oklahoma event clusters
- VSM-MT errors are smaller for OK than KS owning to better azimuthal station coverage
- Comparison of VSM-MT solution for largest M2.8 event in KS cluster shows agreement with HASH-FM and full waveform inversion MT (moment tensor), but only within error. Best fitting solutions appear considerably different
- We will continue to investigate the mechanisms responsible for the key differences in MTs across various methods
- Stress inversion are being completed for VSM-MT results for the Oklahoma cluster and will be compared to the stress inversions from HASH-FM

Questions?

Laura Chiaramonte (EPRI) – lchiaramonte.epri.com

Kayla Kroll (LLNL) – kroll5@llnl.gov

Elizabeth Cochran (USGS) – ecochran@usgs.gov

Jake Walter (OU) – jwalter@ou.edu

APPENDIX

Benefit to the Program

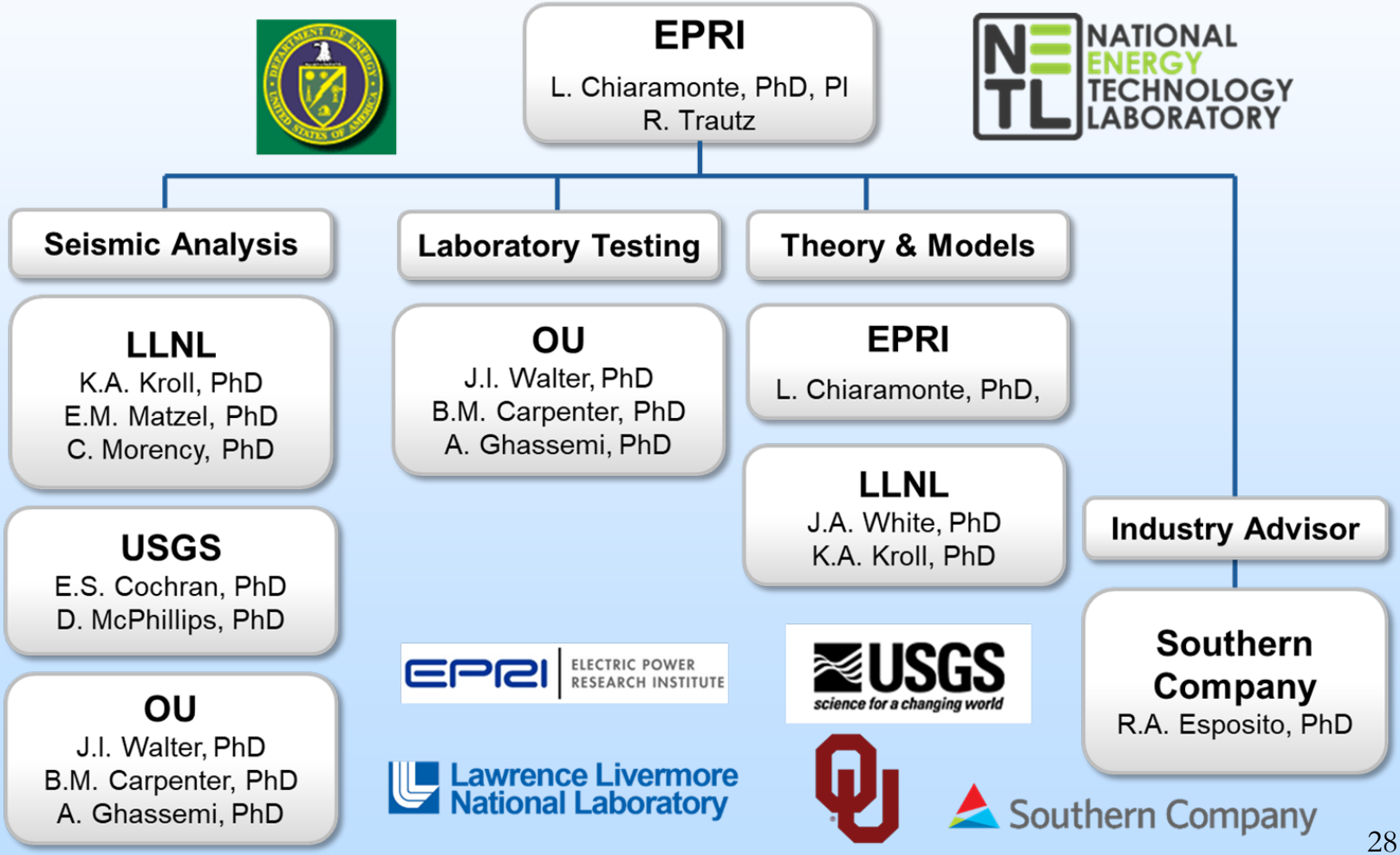
- This project will assist DOE's Carbon Storage program and industry to **address key gaps in experience and knowledge in Carbon Storage Technologies such as the lack of certainty in predicting the geomechanical impacts of pressure migration due to injection into a storage complex**
  - To be able to 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 reduce 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.

Project Overview

Goals and Objectives

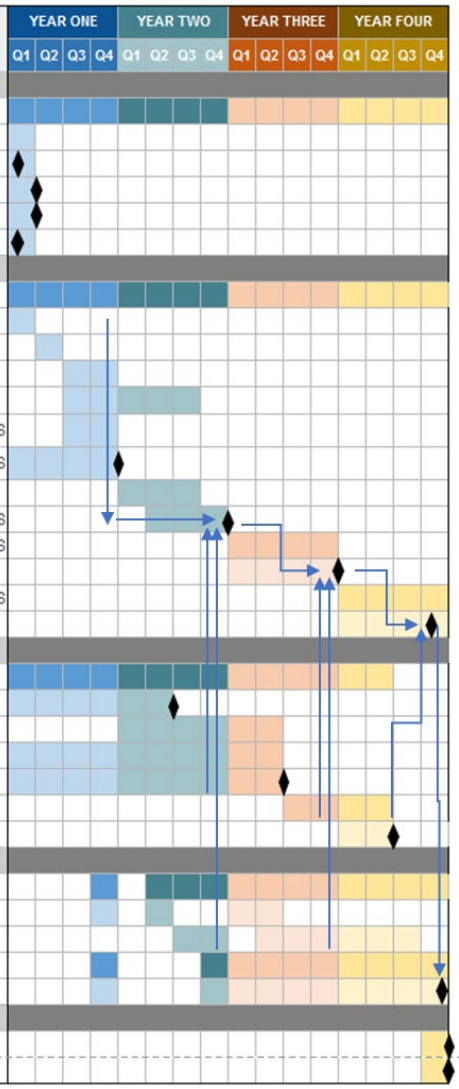
- Develop methodologies to measure the in-situ principal stress, at and below reservoir depths (1.5-6 km), through use of multiple independent, but complementary seismic methods, laboratory verification, and development of theoretical frameworks

Organization Chart



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

- List peer reviewed publications generated from the project per the format of the examples below.

- Skoumal, R. J., Cochran, E. S. (in press). Characterizing stress orientations in southern Kansas, Seismological Research Letters.
- Skoumal, R. J., Cochran, E. S., Kroll, K. A., Rubinstein, J. L., McPhillips, D. (2021). Characterizing stress orientations in southern Kansas, Bulletin of the Seismological Society of America, doi:10.1785/0120200340.
- Brett Carpenter / Will Kibikas submitted 2 chapters of his dissertation
- Skoumal, R. J., Cochran, E. S., Kroll, K. A., Rubinstein, J. L., McPhillips, D. (in press). Characterizing stress orientations in southern Kansas, Bulletin of the Seismological Society of America.
- Kibikas, W.M., B.M. Carpenter, and A. Ghassemi (2019), Experimental analysis of velocity anisotropy in intraplate crystalline basement rocks, AGU National Meeting, MR11B-0032, San Francisco, California
- Chiaramonte, L., Kroll, K., Cochran, E.S., Matzel, E., Morency, C., Skoumal, R., McPhillips, D., Walter, J.I., Carpenter, B.M., Ghassemi, A. and Trautz, R.C., 2019, Refined Principal Stress Estimates for Induced Seismicity in Southern Kansas Based on Seismological Tools and Laboratory Experiments. In AGU Fall Meeting 2019. AGU.