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

Project Number FE0031687

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National Energy Technology Laboratory

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Presentation Outline

- Technical Status
- Accomplishments to Date
- Lessons Learned
- Project Summary
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  - Project Overview
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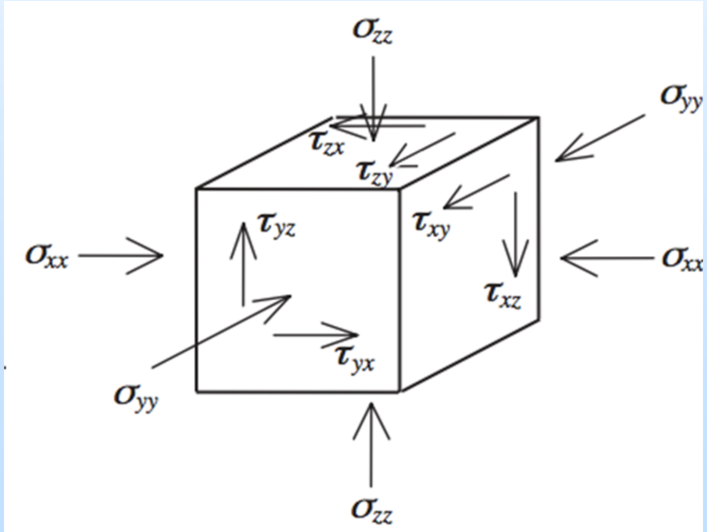
Motivation

- 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

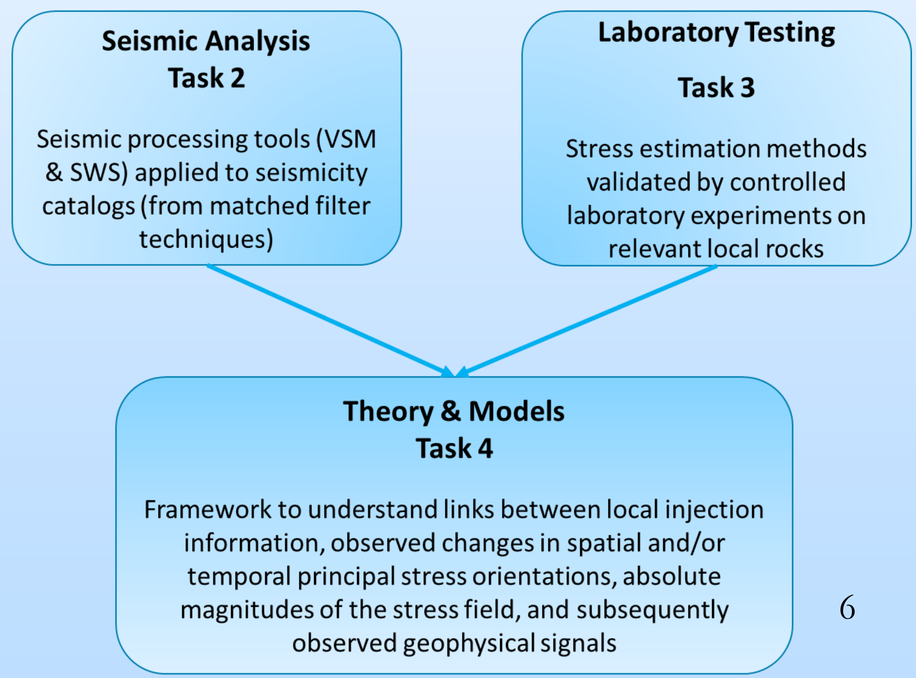
Theory & Models
Task 4

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

Development will be carried on in three stages:

- Method development - Kansas (BP1 & BP2)
- **Method refinement – Oklahoma (BP3)**
- Method validation – California (BP4)



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

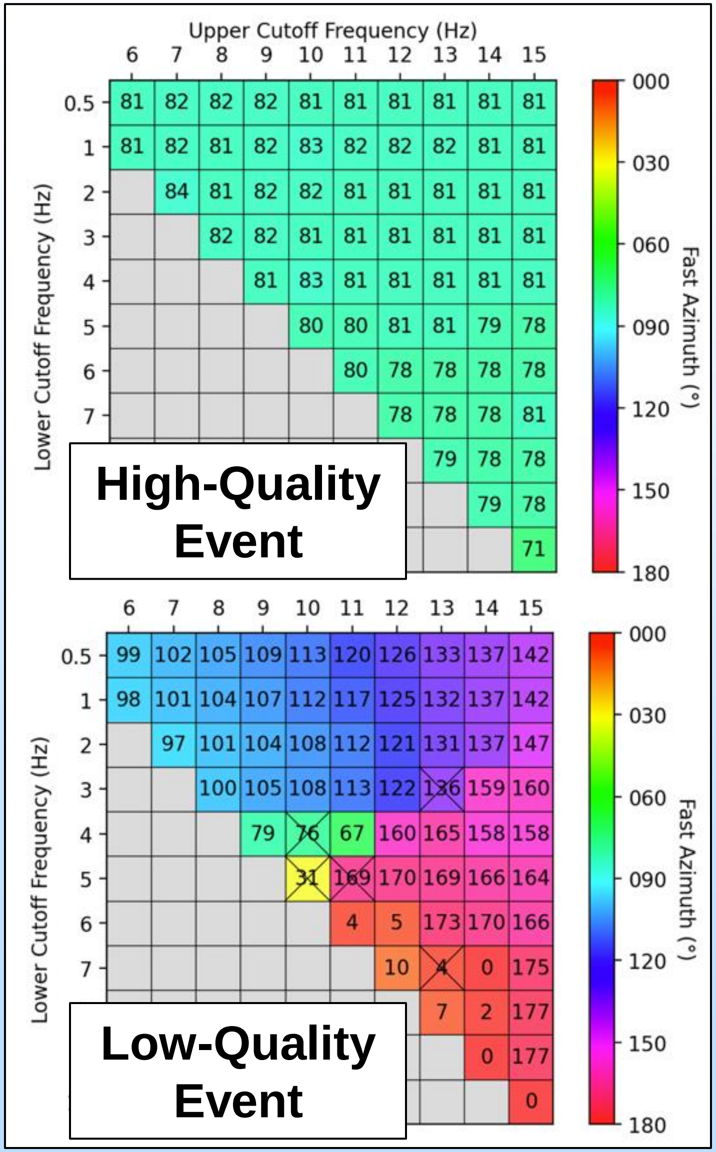
5. **Shear Wave Splitting (SWS):** estimates of the change in crack orientation and aperture due to injection

Accomplishments to Date Task 2: Seismic Analysis

– Task 2: Seismic Analysis
  - Local SWS analysis using microseismicity catalog in OK (USGS);
  - Continuation of VSM analysis from Kansas to OK (LLNL)
  - Machine-learning/AI EQ catalog created for 2010-2021 in Jones area of central Oklahoma (OU)

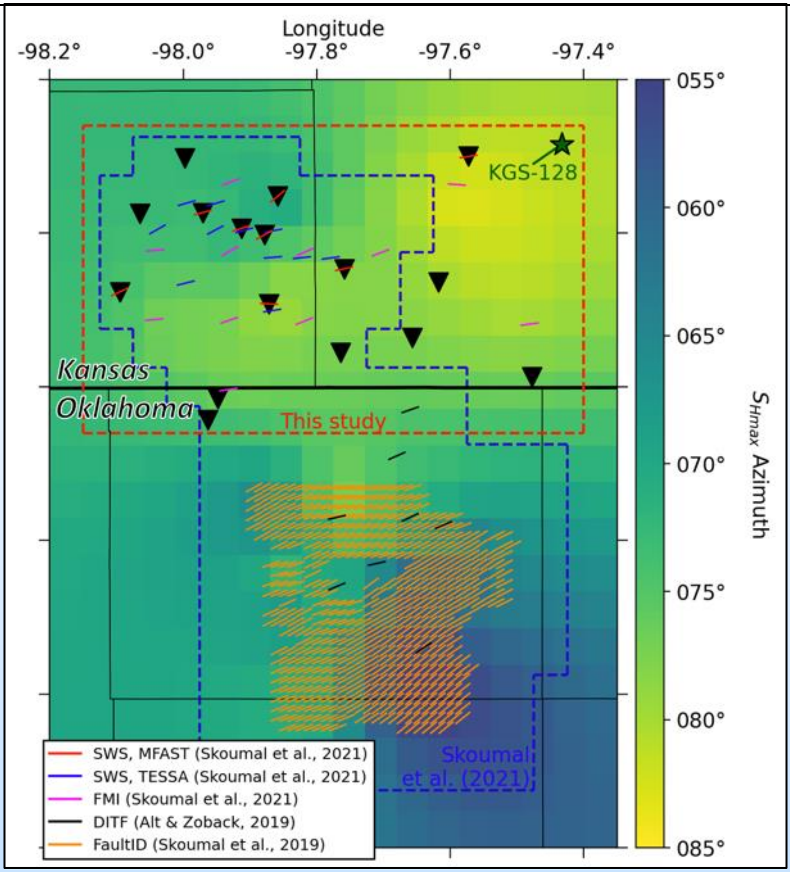
Shear Wave Splitting Methodology

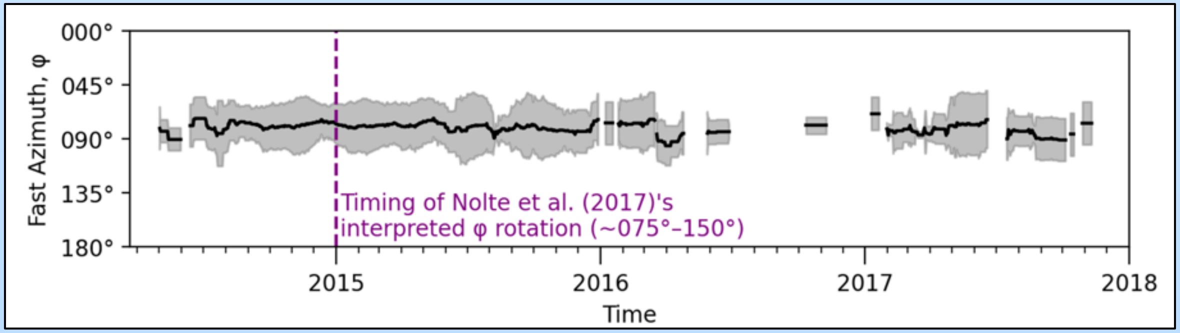
- Grid search to determine (φ, δt) (Silver & Chan, 1991).
- Selecting filter parameters based on Signal:Noise is misguided.
  - Evaluating the stability of SWS measurements across a variety of frequency bands facilitates automatic processing.
- Clustering similar source-receiver paths into linked chains based on waveform similarity allows for temporal variations within families to be more confidently identified.



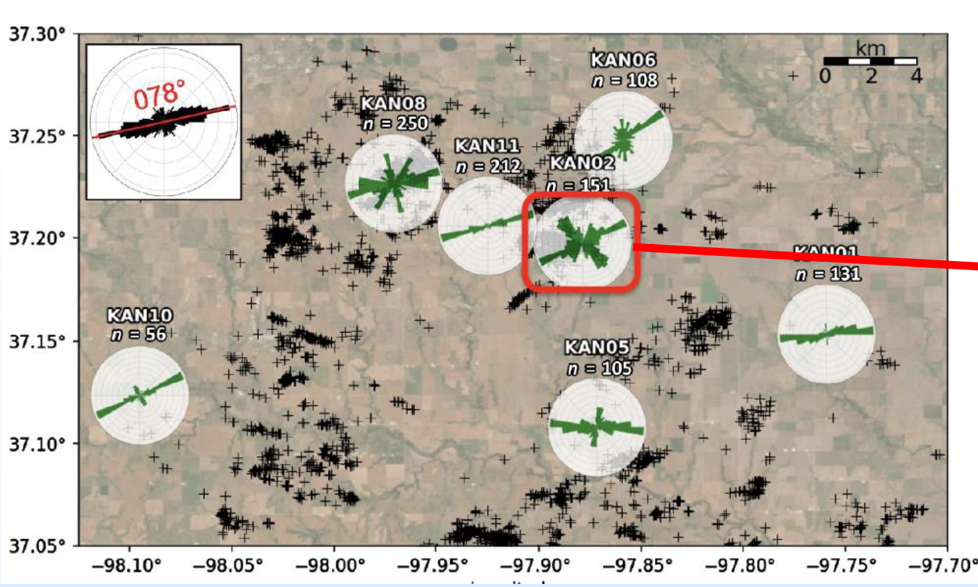
Shear Wave Splitting: Southern Kansas

- 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.

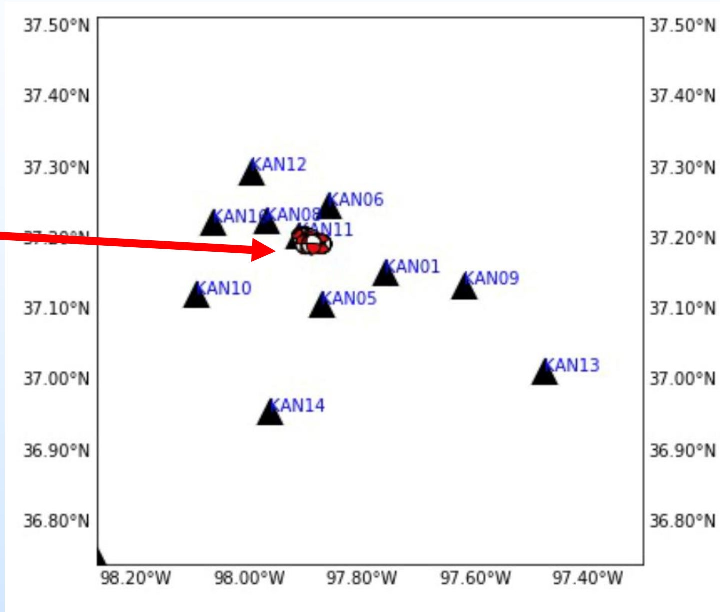




Virtual seismometer method (VSM) for moment tensor inversion

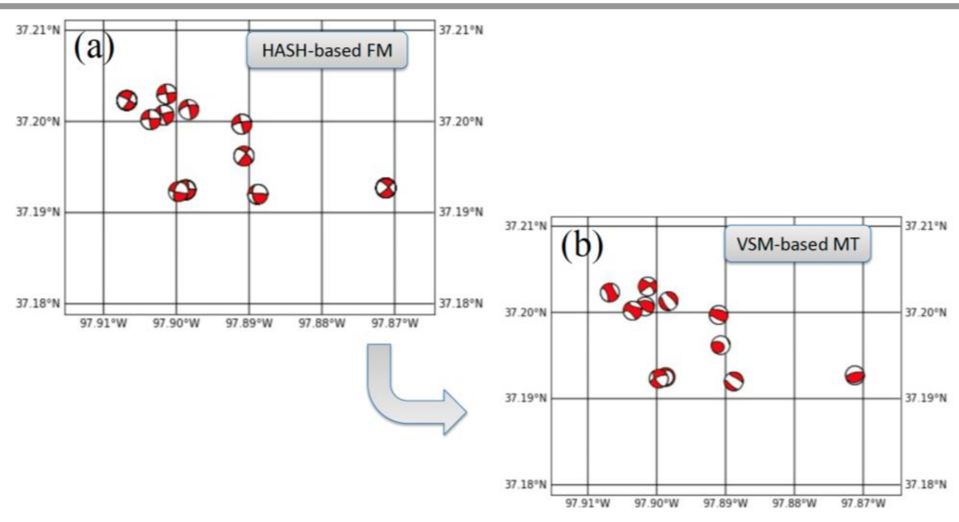


(after Skoumal et al. 2021)

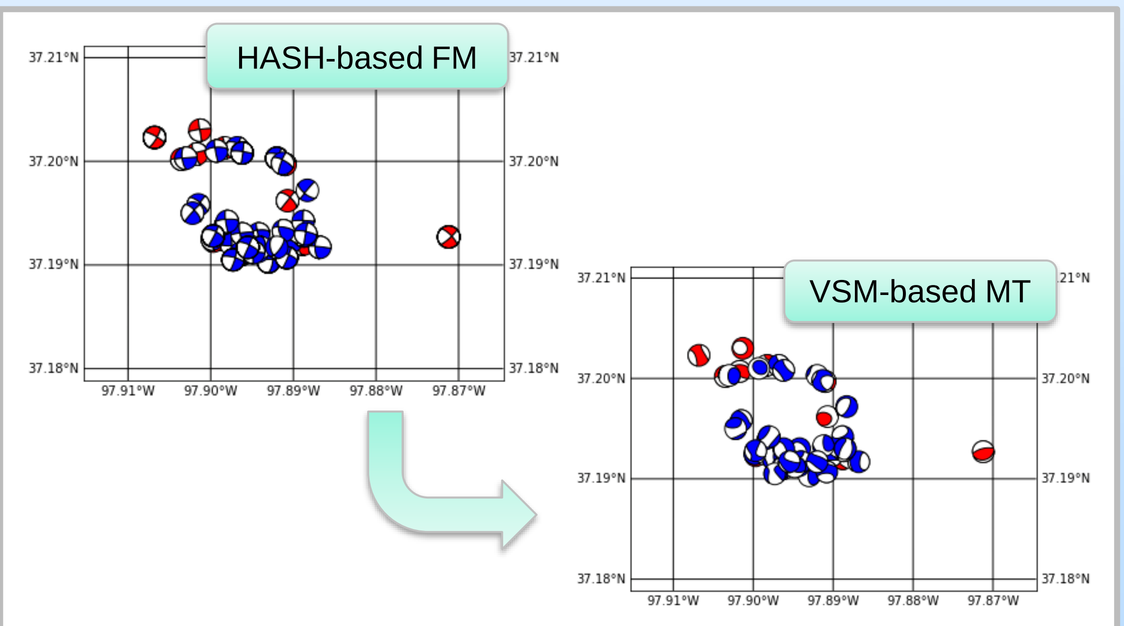


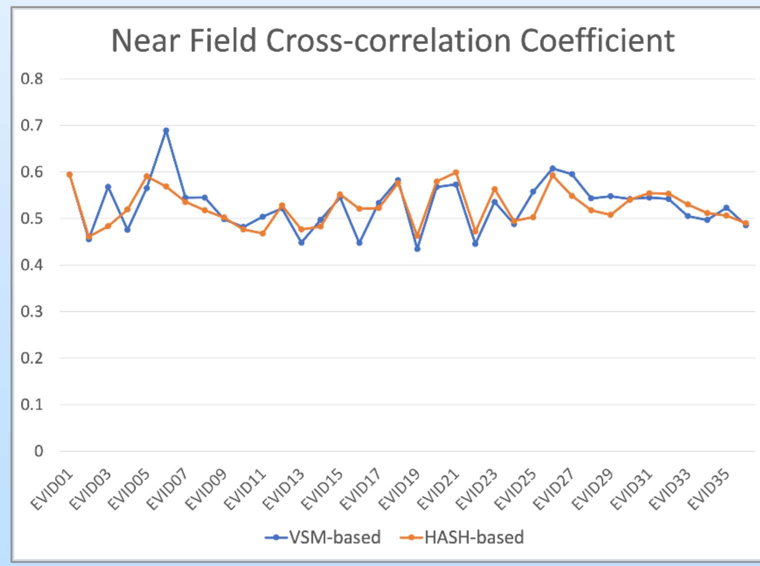
- Identified a subsection in Kansas to assess VSM-based moment tensor (MT) inversion
- Selected 11 clustered events of quality B from a a dense seismicity catalog using the HASH algorithm (Cochran et al., 2018) => 11 events reinverted based on VSM for full MT solution
- Using this virtual seismometer network of 11 events, we reinverted quality C & D events for full MT solution
- Contrary to HASH pure DC solutions, VSM-based MTs show a percentage of non-DC components – *Can we get more information from VSM-based full MTs for stress orientation characterization?*

Virtual seismometer method (VSM) for moment tensor inversion

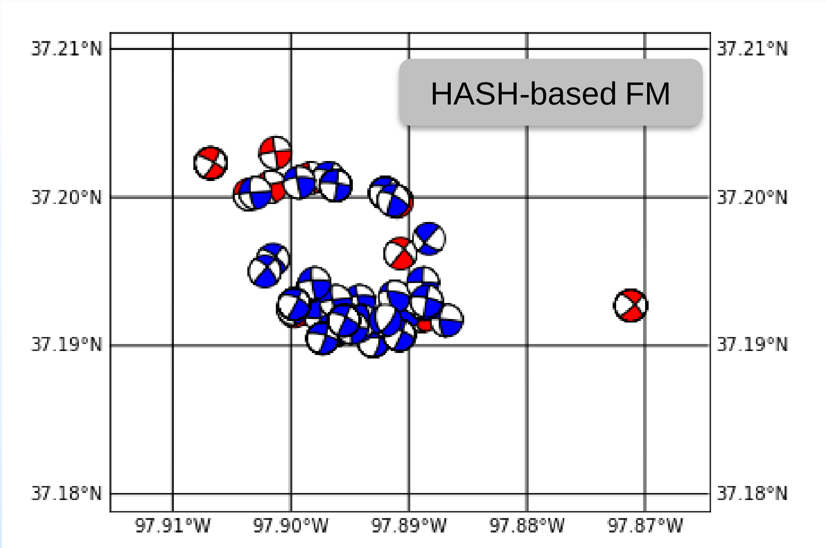


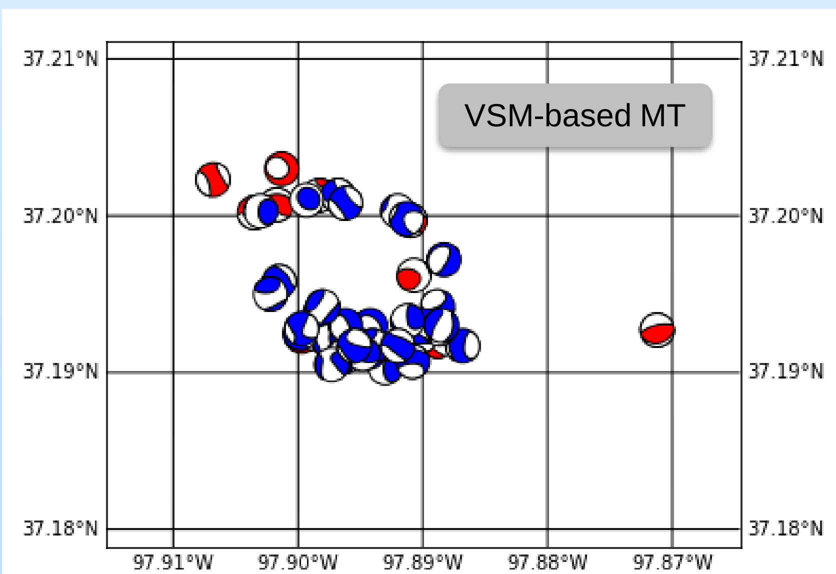
- 11 quality B events reinverted based on VSM
- **These 11 events are then used as a virtual seismometer network**
- 36 quality C & D events are reinverted using the virtual seismometer network

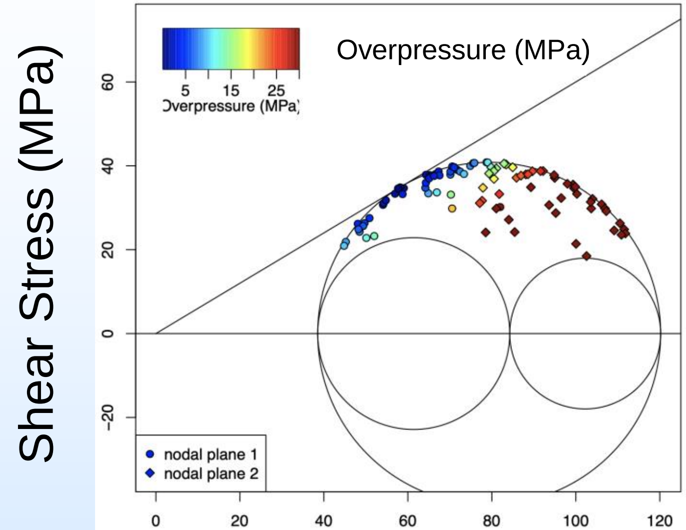


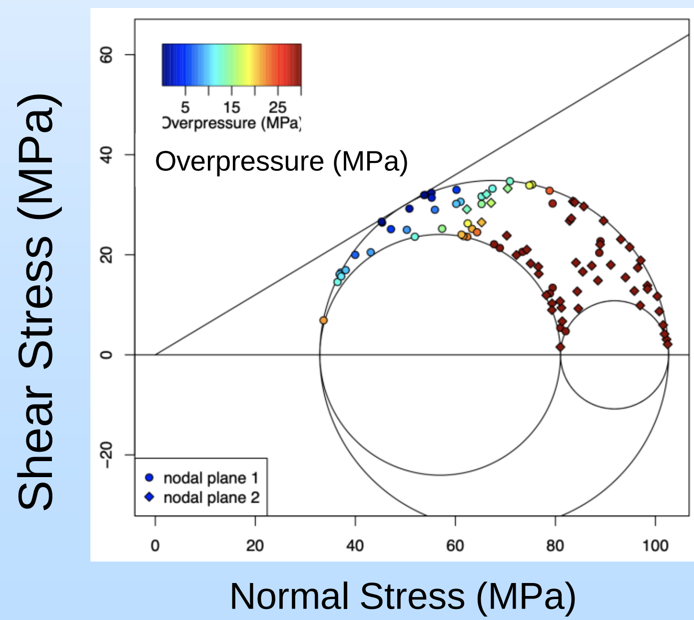


Kansas Stress State from Focal Mechanisms and Moment Tensors



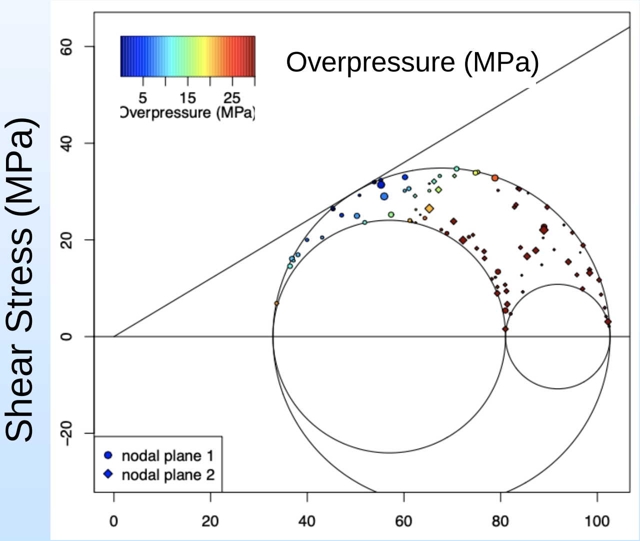






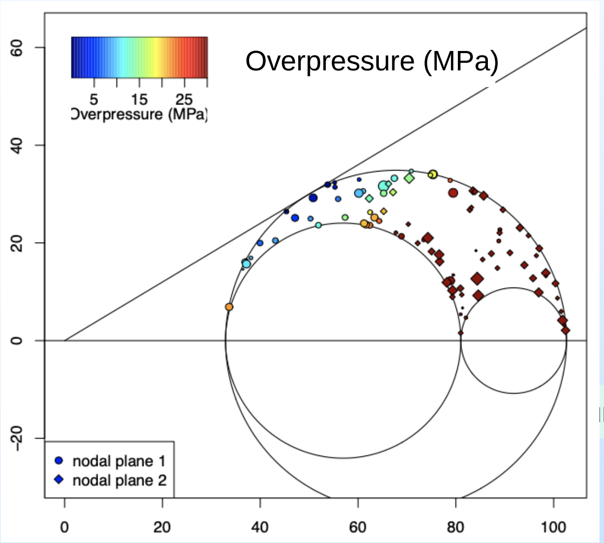
Moment Tensors Provide Additional Information on Kinematics

Scaled by % Isotropic component



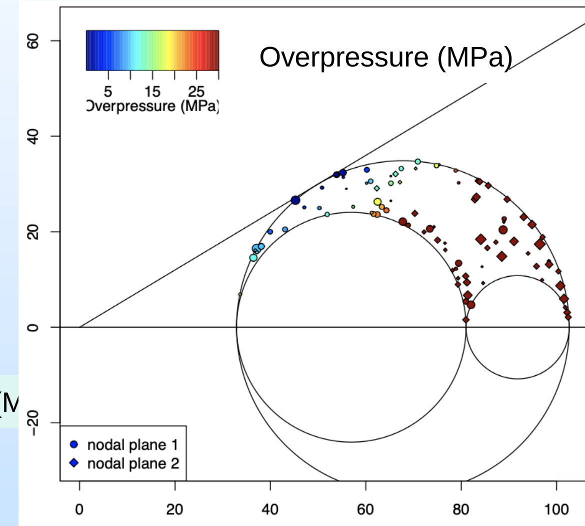
Normal Stress (MPa)

Scaled by % Double-Couple component



Normal Stress (MPa)

Scaled by % CLVD component



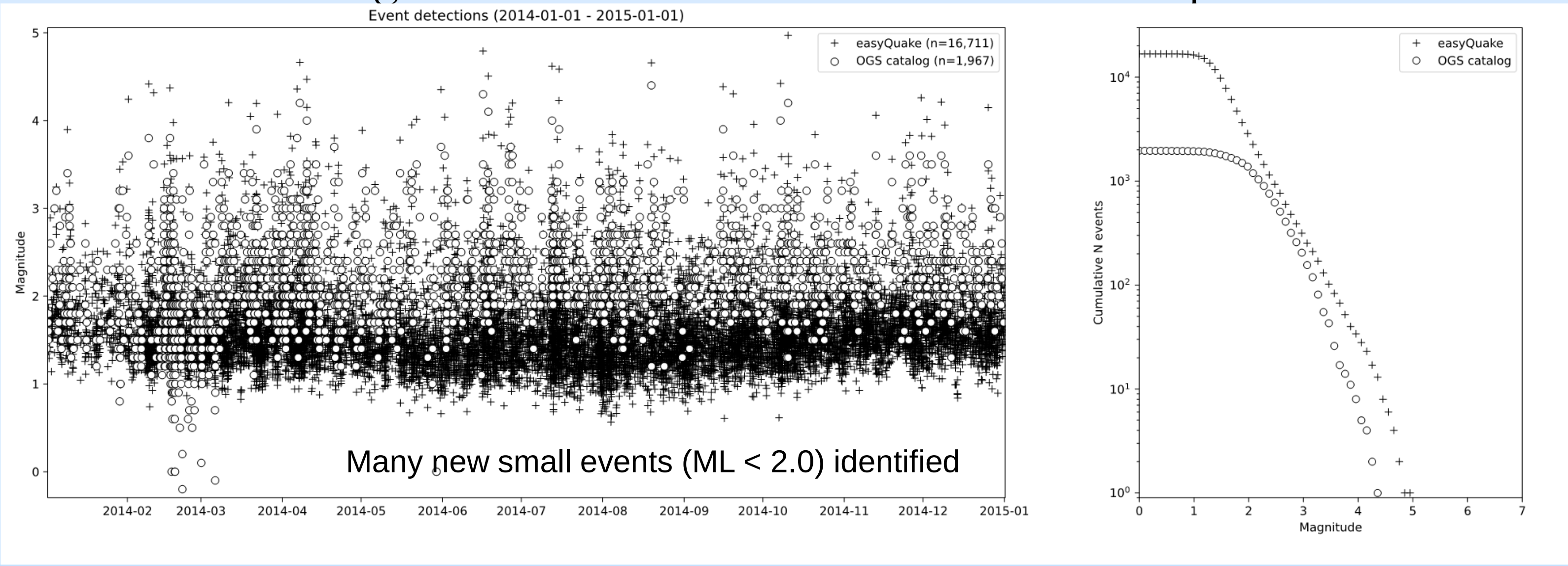
Normal Stress (MPa)

Machine-learning/AI to find smaller earthquakes

easyQuake open-source Python software (Walter et al., 2021): https://github.com/jakewalter/easyQuake

- Catalog created for 2010-2021 in Jones area of central Oklahoma
- 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 shear-wave splitting (USGS) and VSM (LLNL)

Figure below from 2014 shows that it lowers magnitude of completeness by ~1 unit and order of magnitude more event detections for example from 2014



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.

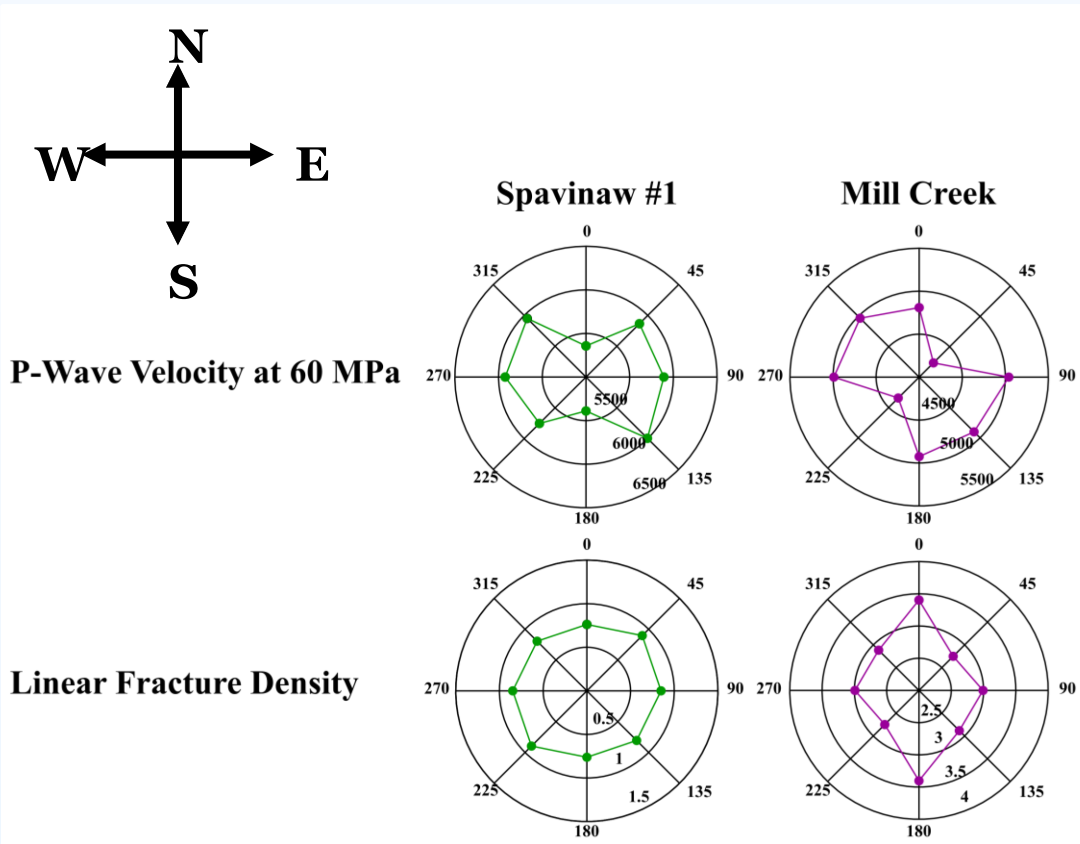
Task 3.2: Synthesis of Petrophysical Observations

- Illuminate regional **basement fracture**

Accomplishments to Date Task 3: Laboratory Testing

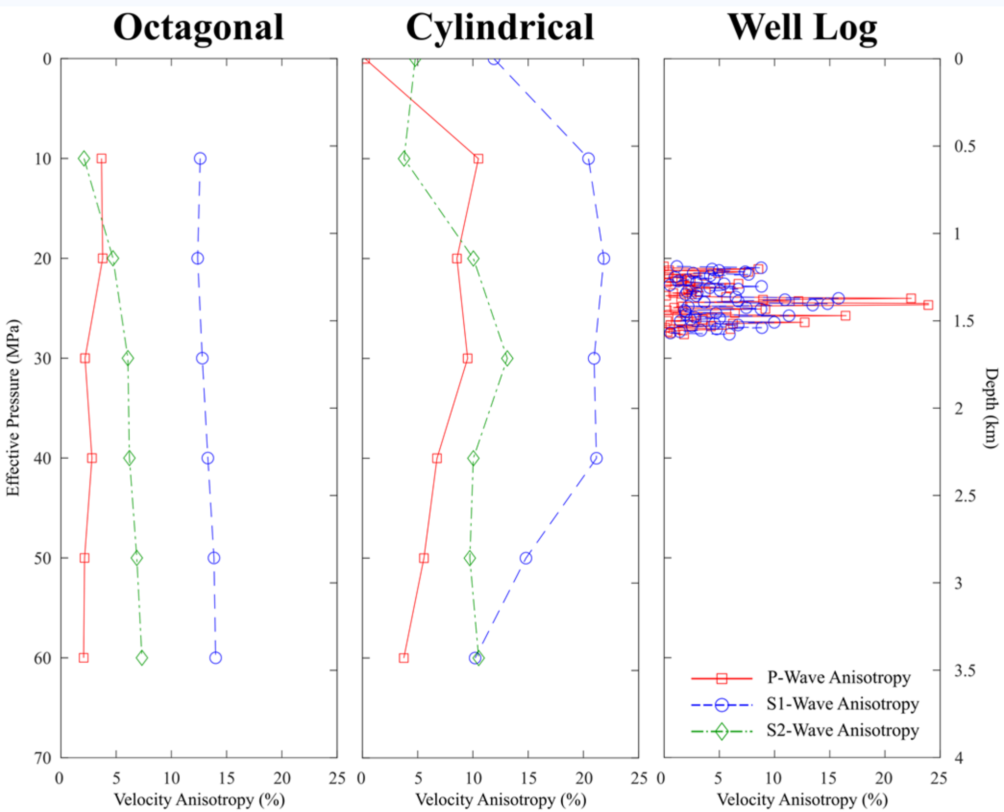
- Velocity anisotropy characterization in crystalline basement rocks of Oklahoma and Kansas using a suite of experimental ultrasonic velocity tests in an isotropic stress field.
- Observations were paired with thin-section characterization of fractures in the vertical and horizontal planes to demonstrate the effect of intrinsic anisotropy on basement rocks.
- Results show there is a considerable degree of velocity anisotropy present in basement rocks at the experimental level, both in the vertical and horizontal directions. 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. Velocity and fracture measurements were related to attempts measure the stress orientations in the field. We determined that, within certain basement 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..

Example of Observed Velocity and Fracture Anisotropy



Velocity and fracture density measurements on oriented samples of the Precambrian basement show that the basement has a measurable horizontal velocity anisotropy and in the case of the Spavinaw sample, preferred microfracture orientations.

Horizontal Anisotropy: Experimental vs. Well Log – Kansas Basement Core



	Octagonal	Cylindrical	Well Log
P-Anisotropy (%)	2.77	6.41	4.63
S1-Anisotropy (%)	13.16	17.31	-
S2-Anisotropy (%)	5.54	8.86	5.11
E_d (GPa)	82.25 ± 3.11	72.58 ± 11.80	66.16 ± 13.77
v_d (-)	0.24 ± 0.01	0.28 ± 0.01	0.25 ± 0.03

- Experimental data is comparable to well log data from KGS 1-32.
- Average horizontal anisotropy is low, but there exist zones of high anisotropy where fractures are likely more prolific.

Theory and Modeling - Task 4

Use results from Task 2 & 3, velocity models, focal mechanism, measured stress rotations, 4 (or 5) stress tensor components, to constrain 6th component of stress tensor

- 4.1 Geomechanical Modeling
- 4.2 Theoretical Framework

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

Lessons Learned

– Research gaps/challenges.
– Unanticipated research difficulties.
– Technical disappointments.
– Changes that should be made next time.
– Multiple slides can be used if needed.

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.

– While our results do not indicate any significant spatiotemporal stress rotation in southern Kansas, both SWS and focal mechanism inversion rely on spatially binning observations. The potential for local rotations (<10x10 km) may not be resolved.

– Preliminary S_{Hmax} orientations in central Oklahoma determined from SWS (N71°E) and focal mechanism inversion (N69°E) are also consistent.

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 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.

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

EPRI
L. Chiaramonte, PhD, PI
R. Trautz

- **Seismic Analysis**
  - **LLNL**: K.A. Kroll, PhD; E.M. Matzel, PhD; C. Morency, PhD
  - **USGS**: E.S. Cochran, PhD; D. McPhillips, PhD
  - **OU**: J.I. Walter, PhD; B.M. Carpenter, PhD; A. Ghassemi, PhD
- **Laboratory Testing**
  - **OU**: J.I. Walter, PhD; B.M. Carpenter, PhD; A. Ghassemi, PhD
- **Theory & Models**
  - **EPRI**: L. Chiaramonte, PhD,
  - **LLNL**: J.A. White, PhD; K.A. Kroll, PhD
- **Industry Advisor**
  - **Southern Company**: R.A. Esposito, PhD

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.