A Non-Invasive Approach for Elucidating the Spatial Distribution of *in-situ* Stress in Deep Subsurface Geologic Formations Considered for CO_2 Storage

DOE AWARD DE-FE0031686

Presented by:

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Presentation Outline

- Introduction
  - Objectives, hypotheses, approach/tasks
- Status/Accomplishments/Lessons Learned/Synergies
  - Task 2
  - Task 3
  - Task 4
  - Task 5
- Project Summary

PROJECT OBJECTIVES
(from FOA)

1. Develop a method(s) for determining the lateral and vertical distribution of the magnitude and orientation of in-situ stresses in the deep subsurface (depths greater than 1500 meters)
2. Conduct verification testing of the method at a field site
3. Attempt to achieve an improvement (technical and economic performance) over the state-of-the-art methods for determining in-situ stresses

Project Hypotheses

1. it is possible to determine orientation of stress (for an area) from analysis of conventional seismic data
   - process converted mode data (Sv-P) contained in conventional (P-wave) seismic data to produce S_fast and S_Slow data which indicate orientation of S_{Hmax}
2. It is possible to estimate the magnitude of stress from seismic-derived velocity data (Vs, Vp, etc.) using results of laboratory rock tests that establish relationship between stress and velocities
3. It is possible to extend the areal coverage of the seismic-derived stress results using numerical modeling

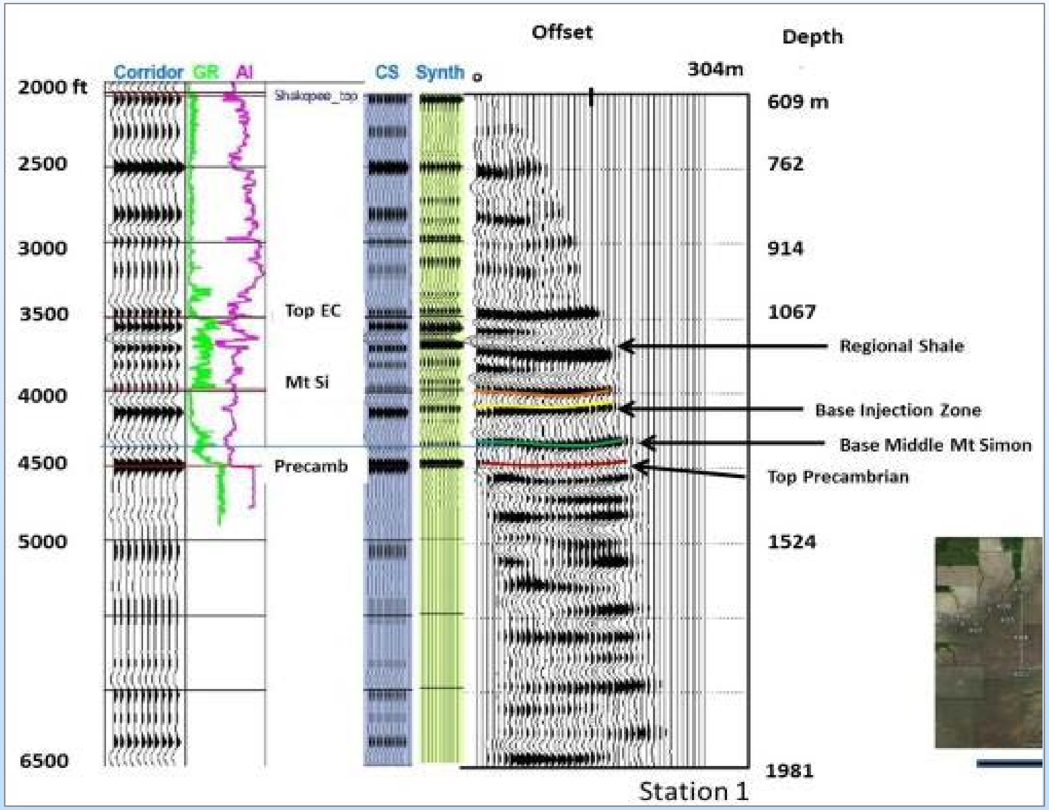
Project Method/Tasks

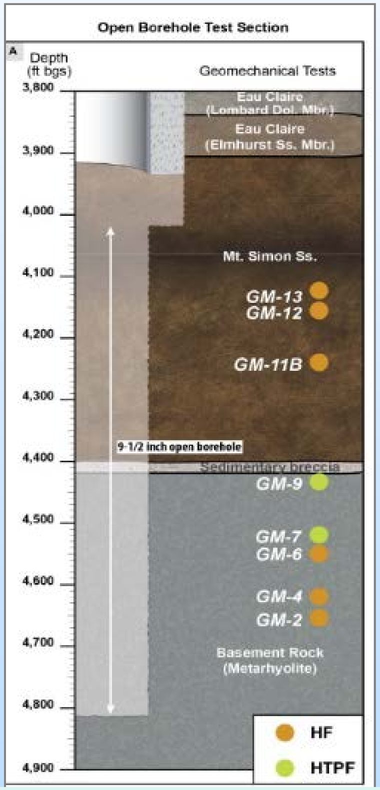
- Task 1 – Project Management
- Task 2 – Acquire seismic data for two field sites and process the data to extract P and S-Wave Stress azimuth.
  - Futuregen2 site Illinois
  - Michigan Core Energy Site
- Task 3 – Conduct laboratory TUV experiments on multiple rock types to determine the relationship between velocity data (Vp/Vs, Vs fast/Vs slow) and magnitude of in-situ stresses (SHmax/Shmin).
- Task 4 – conduct in-situ stress tests in Michigan well to obtain field data to verify method
- Task 5 – stress modeling to predict stress orientation and magnitude beyond the area with seismic data.

Task 2a – Seismic Processing Futuregen2 (Illinois) Site

- two seismic surveys to demonstrate the method
  - Futuregen2 (Illinois) Vertical Seismic Profile (VSP) Survey
  - Michigan Perch 3D seismic survey (MI)

Verification Well





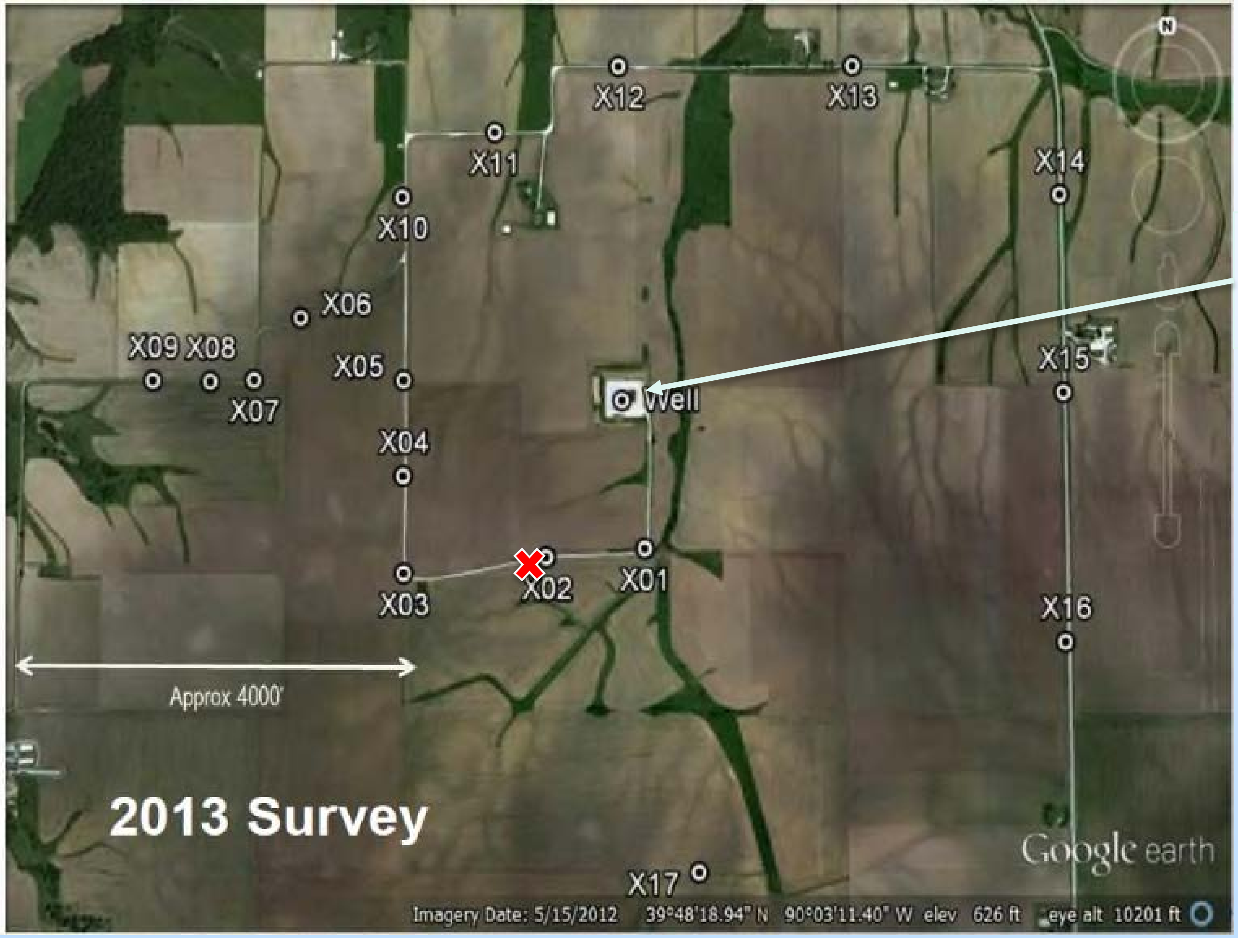
Futuregen2 VSP image Showing Mount Simon Sandstone (Reservoir) and Overlying Eau Claire Shale Caprock.

Characterization well showing geology and location of HF tests (orange dots) and HTPF tests (green dots) with Shmin and Shmax measurements in the Mount Simon Sandstone and Pre-Cambrian Granite

Status/Accomplishments Task 2 –

- Acquired VSP data from Schlumberger
- Determined data is complete and of useable quality (S-wave data esp.)
- Performed wavelet rotational analysis for evidence of S_fast and S_slow and S_{hmax} orientation

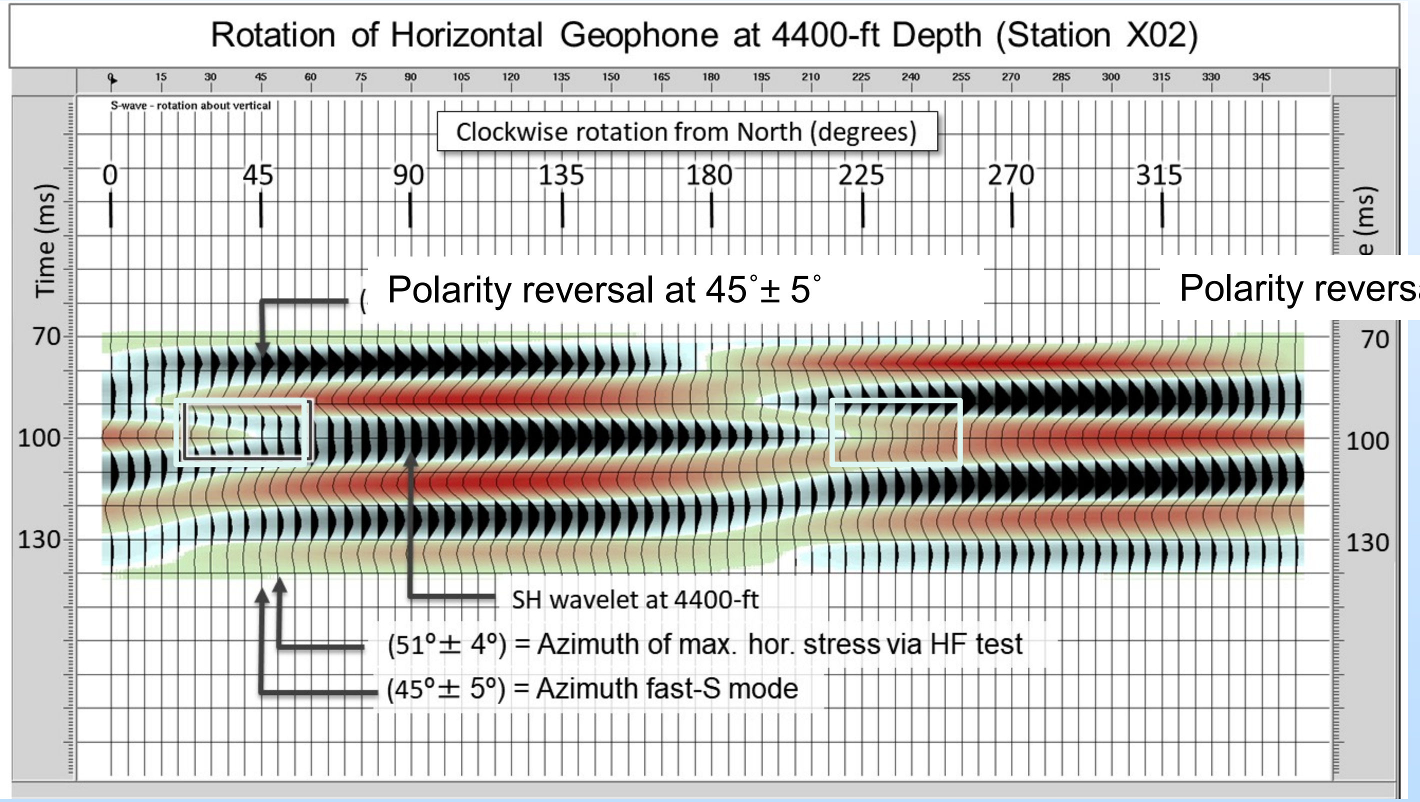
VSP Source Positions



VSP Receiver Array
and Zero-Offset Source (ZVS

Wavelet Rotation Processing for Stress Orientation

- Look for evidence of polarity “switching” that is indicative of anisotropy (S-Fast and S-Slow)
- Polarity reversals should occur 180 degrees apart
- Fast-S mode polarizes in the same azimuth as stress induced extensional fractures (S_{Hmax}).



Results of Rotation Analysis

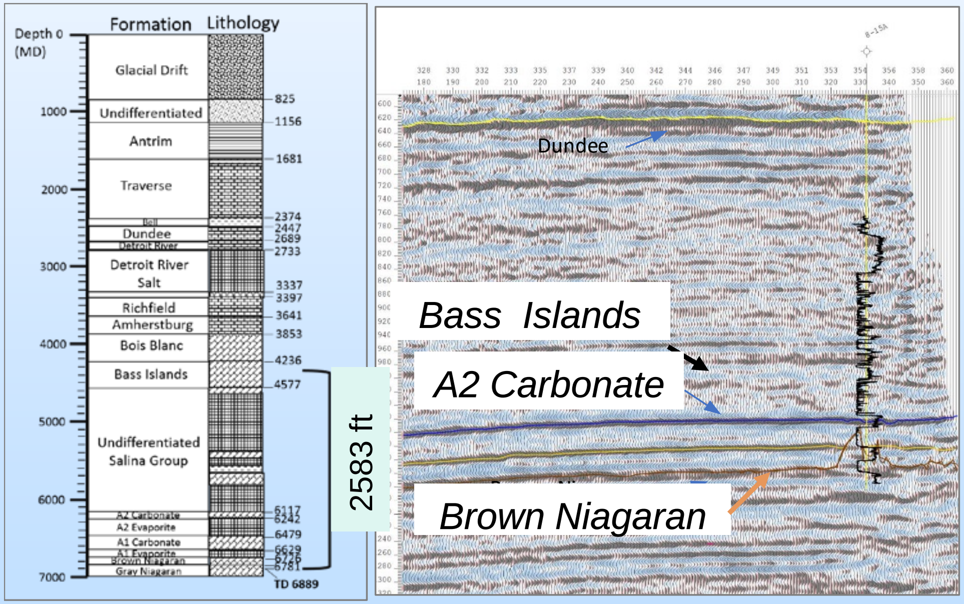
- For deepest geophone station (4400 ft.) almost half of the (14) source stations yield S_{Hmax} of 50 degrees (±5 degrees) and about half yield 60 degrees (±5 degrees).
  - results agree with hydraulic fracture results from the verification well that indicate S_{Hmax} is 51 degrees (±4 degrees)
- For one shallower geophone (3400 ft) – again did rotational analysis for all 14 VSP source points and results were similar
- For a single source (Zero Offset VSP), geophones were analyzed at successively shallower depths (1,000 ft increments) and produced consistent results (i.e., S_{Hmax} is 50 degrees with error estimates of ±5 degrees along the total well depth).

Lessons Learned

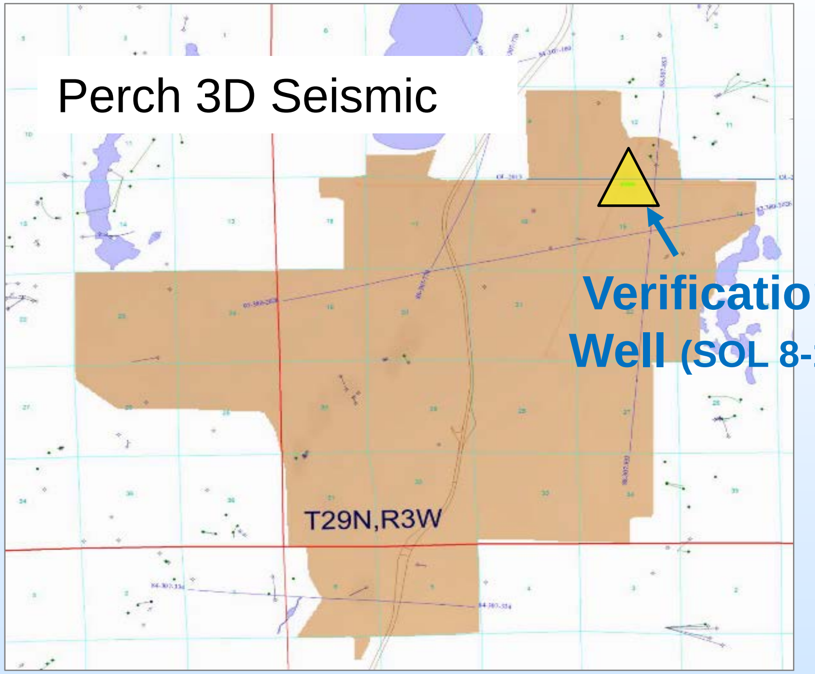
- Rotation analysis shows we can use:
  - offset source stations and a single deep geophone station to get a volumetric picture of S_{Hmax} azimuths around a VSP well
  - a zero-offset source and geophones at various depths to determine if rotation of direct-S wavelets indicate S_{Hmax} changes with depth (i.e. geological age).
- S mode undergoing a polarity reversal can be either a slow-S mode or a fast-S mode
- need a ground truth S_{Hmax} value to calibrate which polarity reversals of direct-S are associated with fast-S modes.
  - In-situ stress measurements

Task 2b – Seismic Processing (Michigan Site)

- Goal is to demonstrate (stress mapping) method at two sites with seismicsurveys
  - Futuregen2 (Illinois) Vertical Seismic Profile (VSP) Survey
  - Michigan Perch 3D seismic survey (MI)



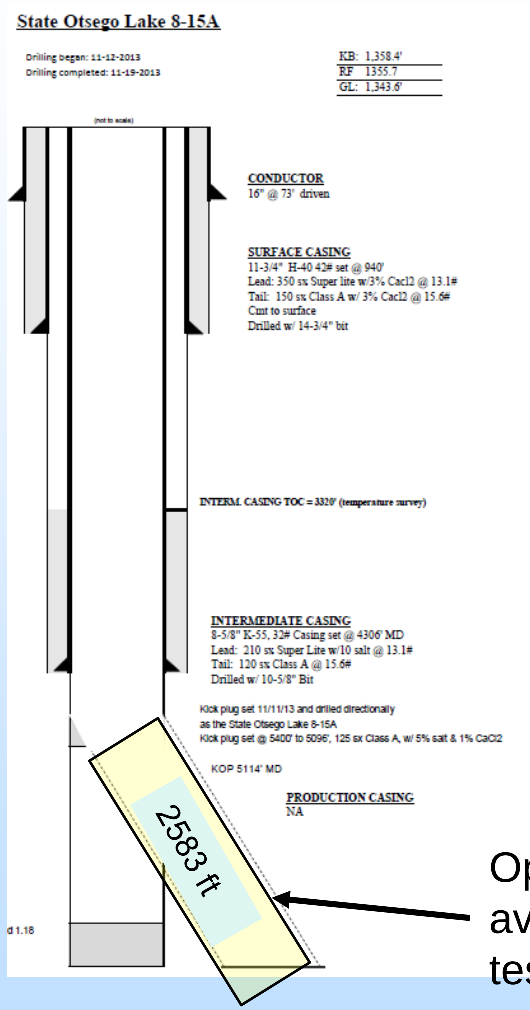
Well SOL 8-15 A *schematic showing geology exposed in the open borehole interval; (right) Seismic P-Wave Image from Perch 3D Seismic Survey showing well sonic log*



7 miles x 6 miles area high-quality 3D seismic survey acquired by Core Energy.

Currently, the 3D seismic data is being re-processed since the original processing only included P-wave data whereas this study requires S-wave data.

Task 4 – Well Testing



Verification data to be collected

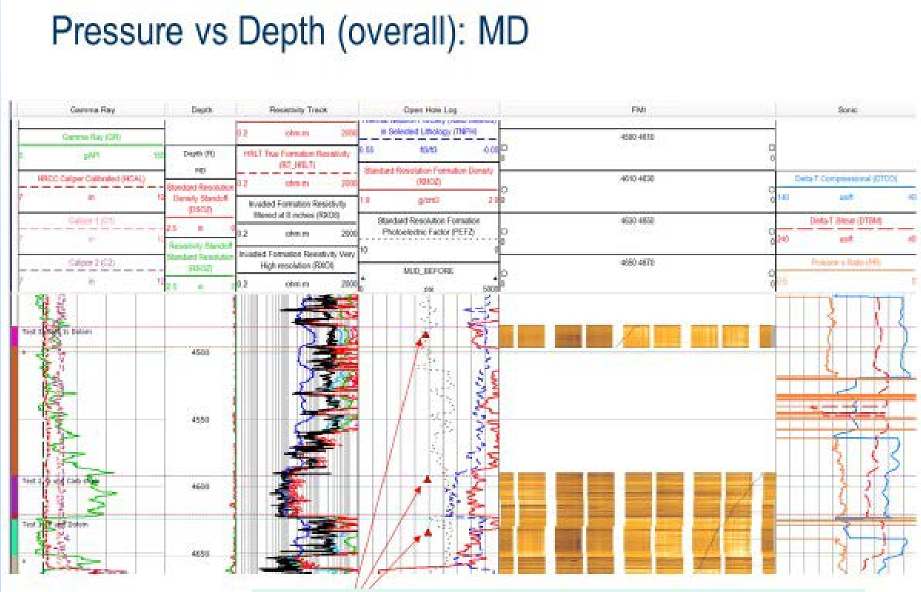
- Routine Geophysical logs (lithology)
- Advanced Geophysical logs
- Shmin magnitude and orientation; Shmax orientation
- Core samples for routine/rock properties

Open borehole section available for logging, coring, testing

Goal is to Obtain Stress Measurements from the SOL8-15A Well to verify stresses derived from seismic data and collect data to support model

Status/Accomplishments – Task 4

- Field Work Completed July 26 – Aug 2
- Well logging: basicsuite, image (resistivity type) log/sonic scanner
- Core (sidewall) collected from 20 depths
- 3 miniature (hydraulic) fracture (mini-frac) tests to determine S_{hmin} and S_{HMAX} (orientation)
- Log/Test interval was 4296 to 5300 ft
- Borehole was not accessible below 5300 ft.



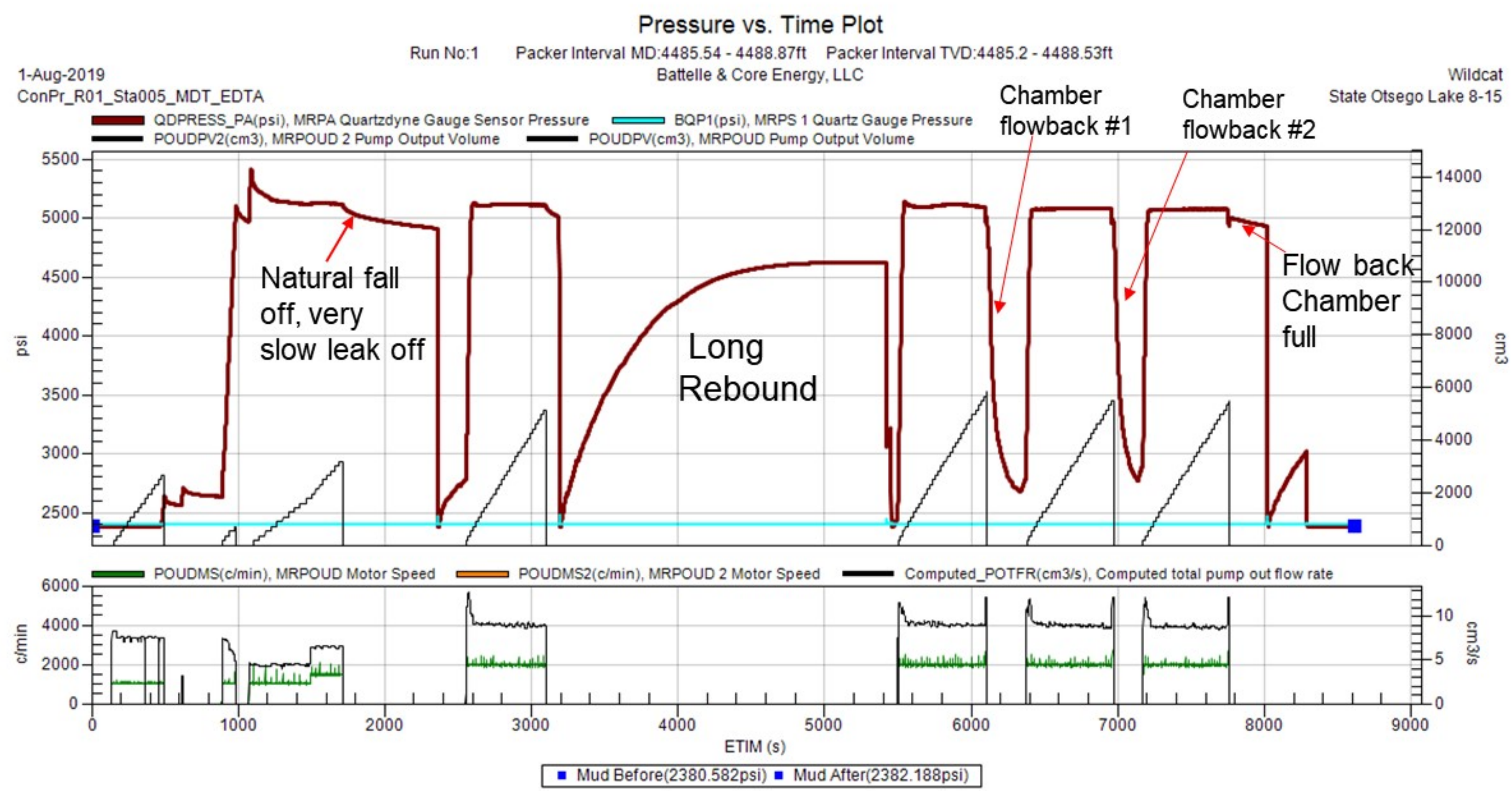
3 Mini-Frac Test Stations

- Mini-frac analysis completed
- Log processing currently underway
- Lab core awaiting testing

Example Mini-Frac Test

Station #3 Overview

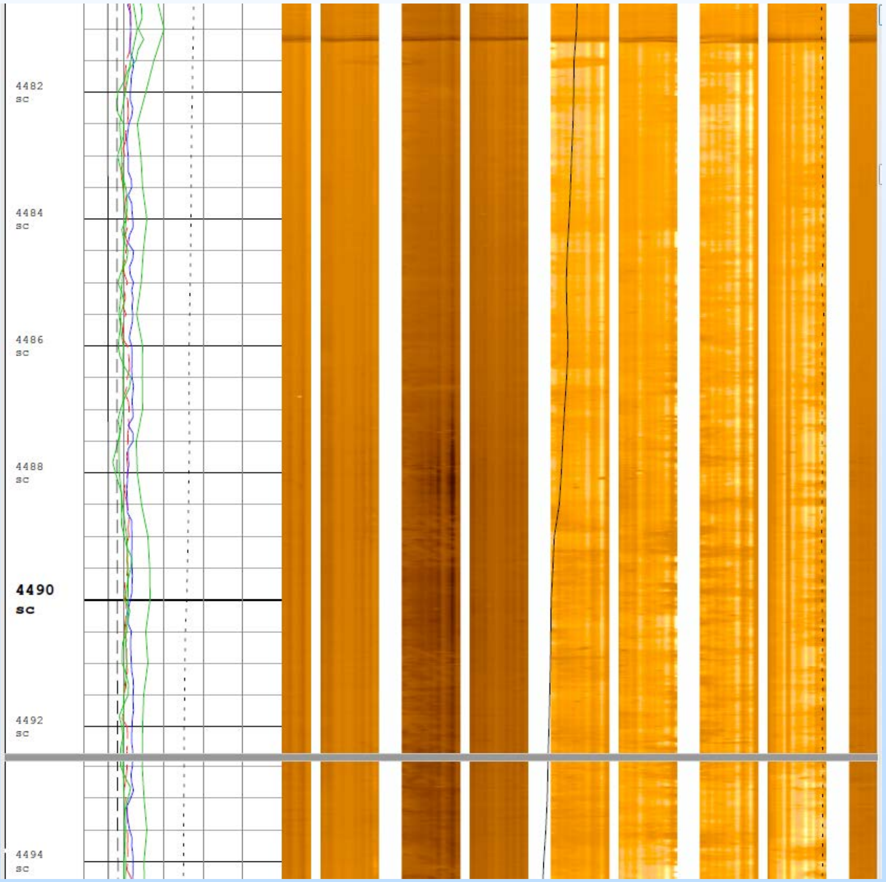
Best estimates:
Breakdown pressure : 5420 psi
Propagation pressure: 5110 - 5130 psi
Closure pressure: 3379 - 3423 psi



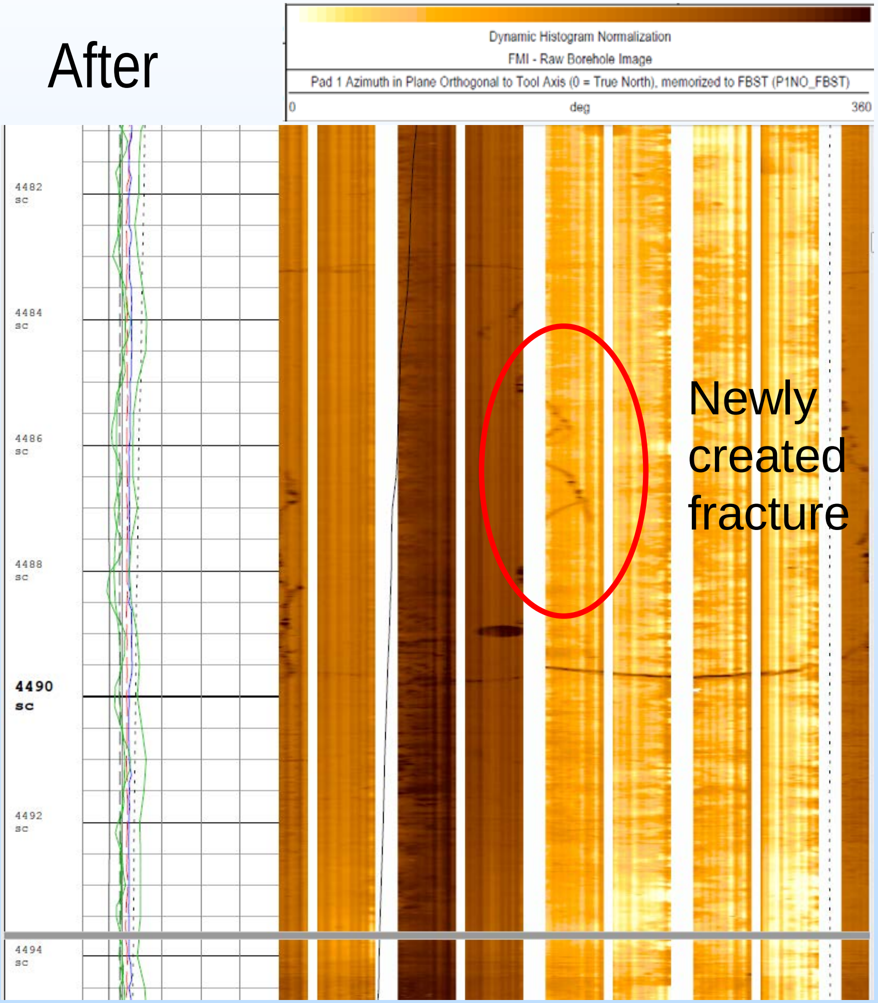
Station 3
4485.5 – 4488.9 ft
Bass Is. (Dolomite Stringer)

Orientation: approx 180˚ (North-South)

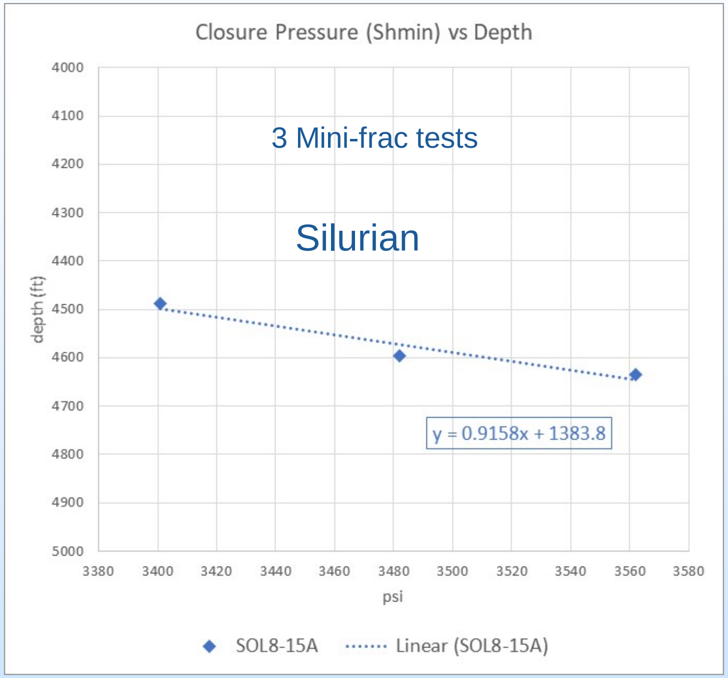
Before

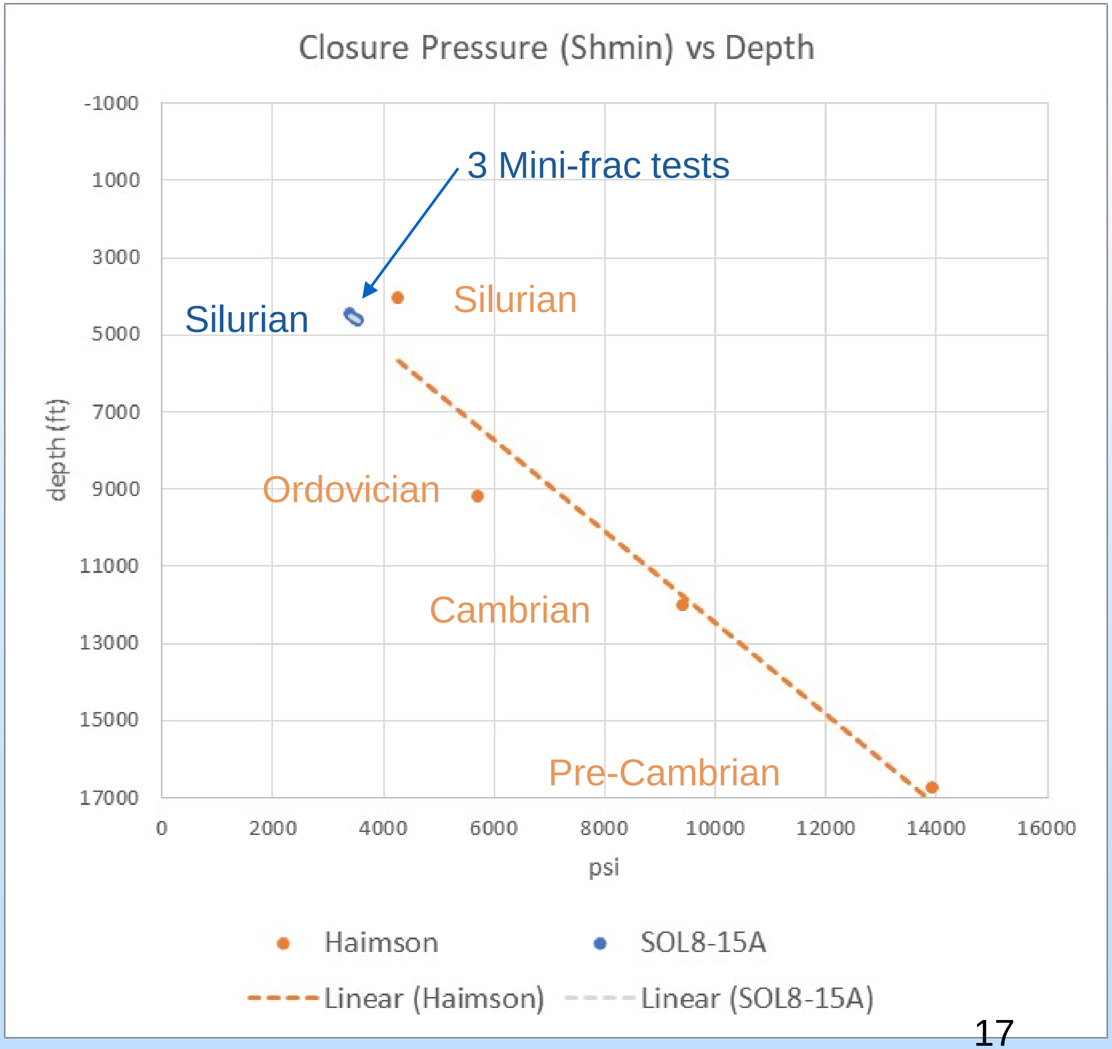


After



Closure Pressures (S_{hmin}) from Mini-Frac Tests Consistent with Haimson Data

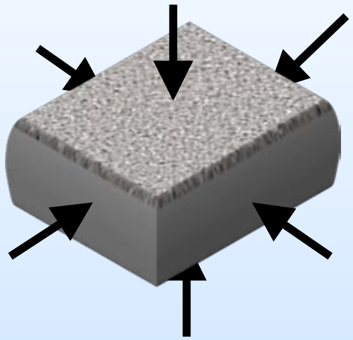




Task 3 – Laboratory TUV Experiments

- Goal is to determine relationship between triaxial stress (direction and magnitude) and ultrasonic velocities (Vp, Vs, Vp/Vs ratio, Vsfast, Vsslow).
- Results will be used to attempt to relate seismic derived velocity data to stress magnitude
- Multiple rock types will be tested including samples from the two test sites (catalog).

Stress-induced Anisotropy



limited laboratory work has been done to characterize stress-induced anisotropy under true tri-axial stress condition.

Status/Accomplishments

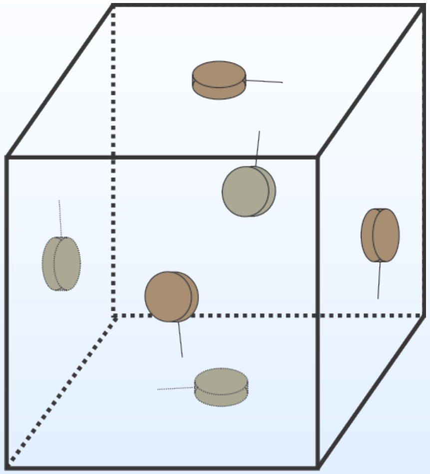
- **Test specimens**
- obtained rock specimens from FutureGen core at DOE core repository (Eau Clair {Lombard} formation, Upper Mount Simon, Lower Mount Simon, and Precambrian basement.
- Obtained representative rock sample from Western Michigan Core Repository for carbonate reservoirs, confining layers, and salts in the Michigan Basin.
- **Test apparatus**
- Designed and implement a transducer array to measure wave speeds
- Designed a fixture and a platform for mounting the system in the true tri-axial cell that helps stopping the sensors from unwanted movements.
- Started using tri-axial load frame to validate data for Berea sandstone, Granite, Aluminum, and Agra red sandstone under confining stresses.
- **Data interpretation software tools**
- Developed a model for interpreting wave speeds to characterize the linear elastic stiffness tensor for an orthotropic material.
- Developed MATLAB code to process waveform data from ultrasound tomography equipment to extract necessary wave speeds and frequency-dependent attenuation data.
- Developing signal processing techniques: filtering signals, fast-Fourier transformation, and representing signals using spectogram.

Lessons Learned

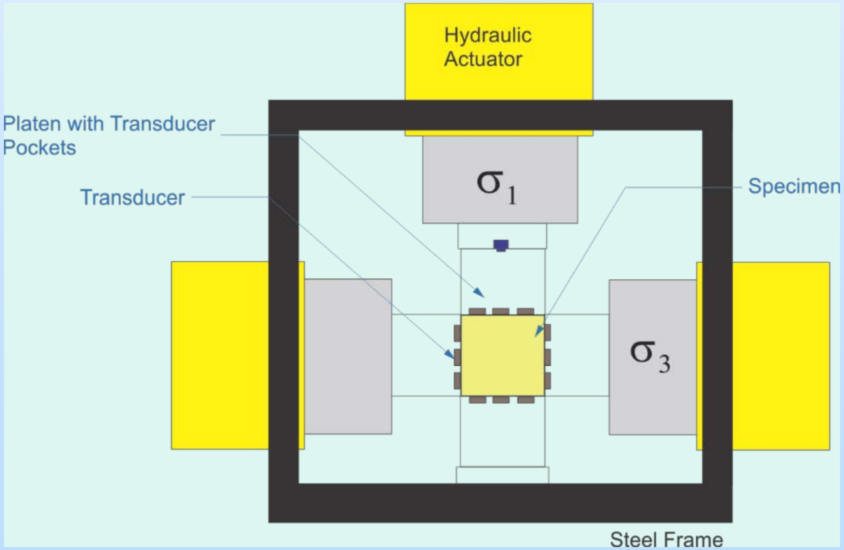
– **Unanticipated research difficulties:** Difficulties on distinguishing P, fast, and slow S waves in small samples.
  Initial data analysis: Waveform definitely changes under different confining loading in both time and frequency domain. Therefore, the wave speed will change under loading which implies the stress-induced anisotropy.

Test Apparatus

- Independent 3-axis control
- Up to 500 MPa on 60 mm cubic specimens

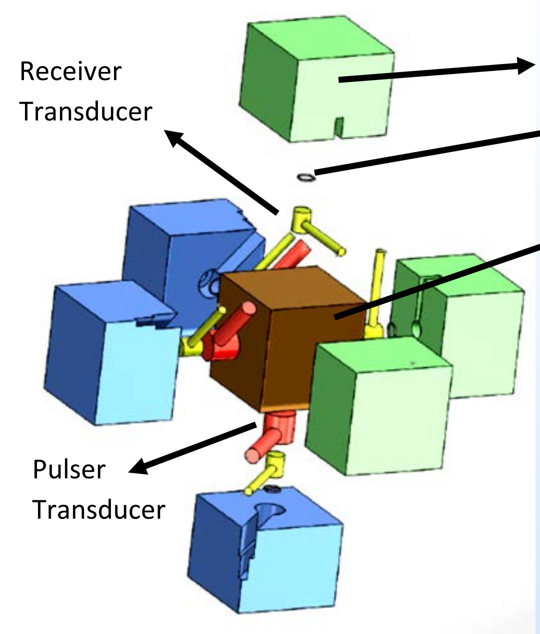


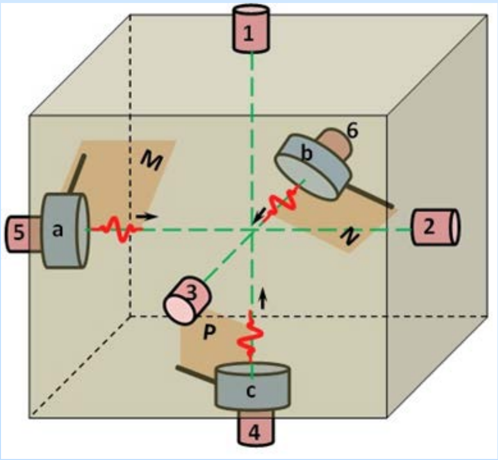
- True triaxial (“polyaxial”) confinement

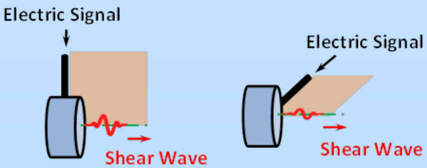


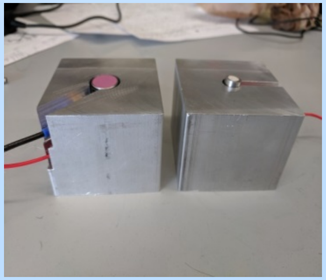
- Multi-directional measurement of P- and S- wave ultrasonic velocity.
- 60mm cube specimen, 5 mm transducers
- 4-8 transducers per side
- 128 ray paths
- 0.1-5 MHz

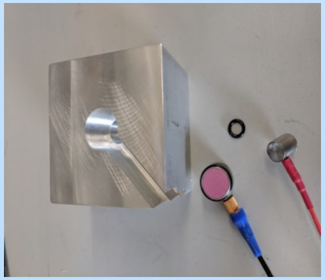
Test Apparatus (cont'd)



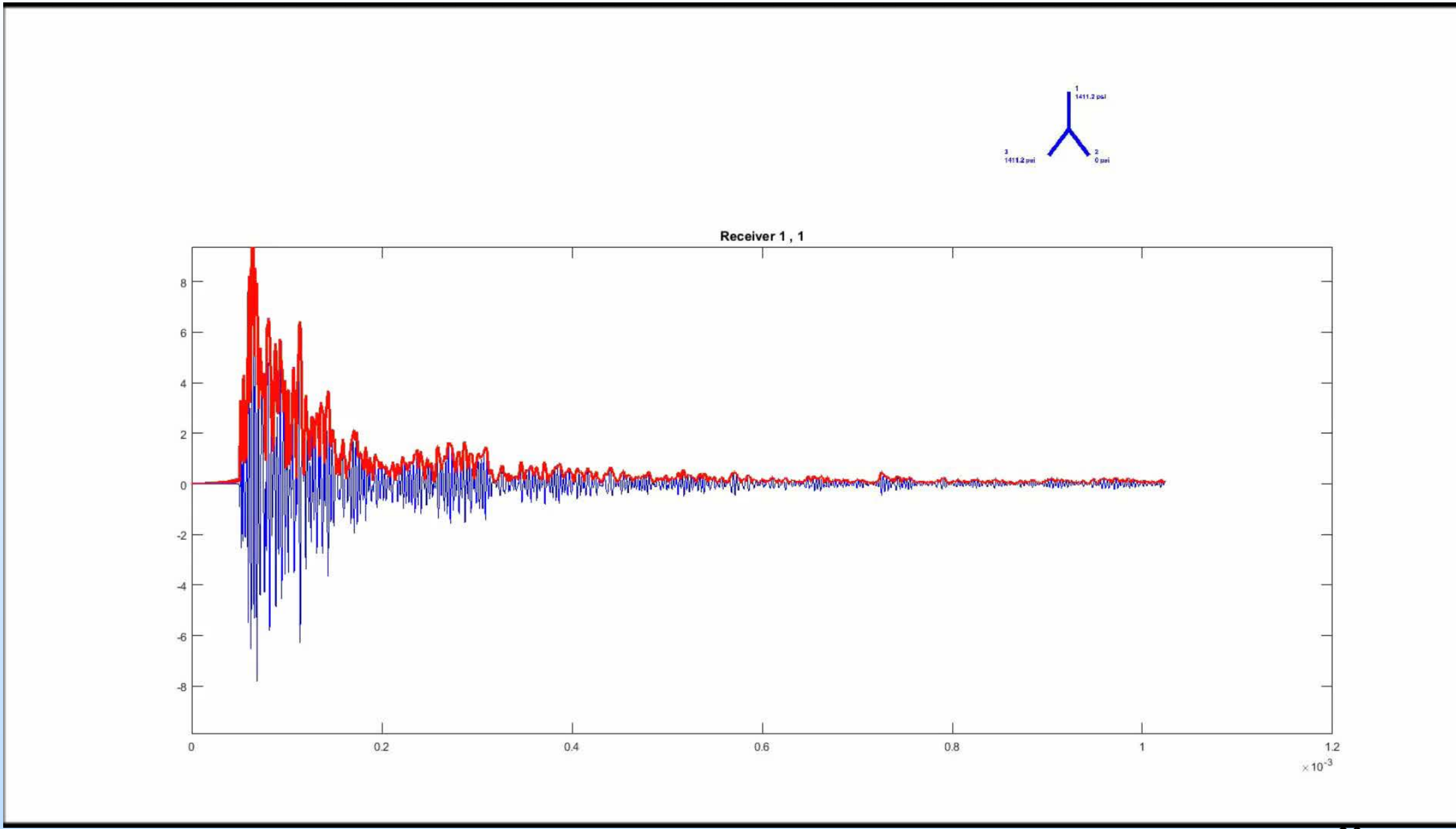




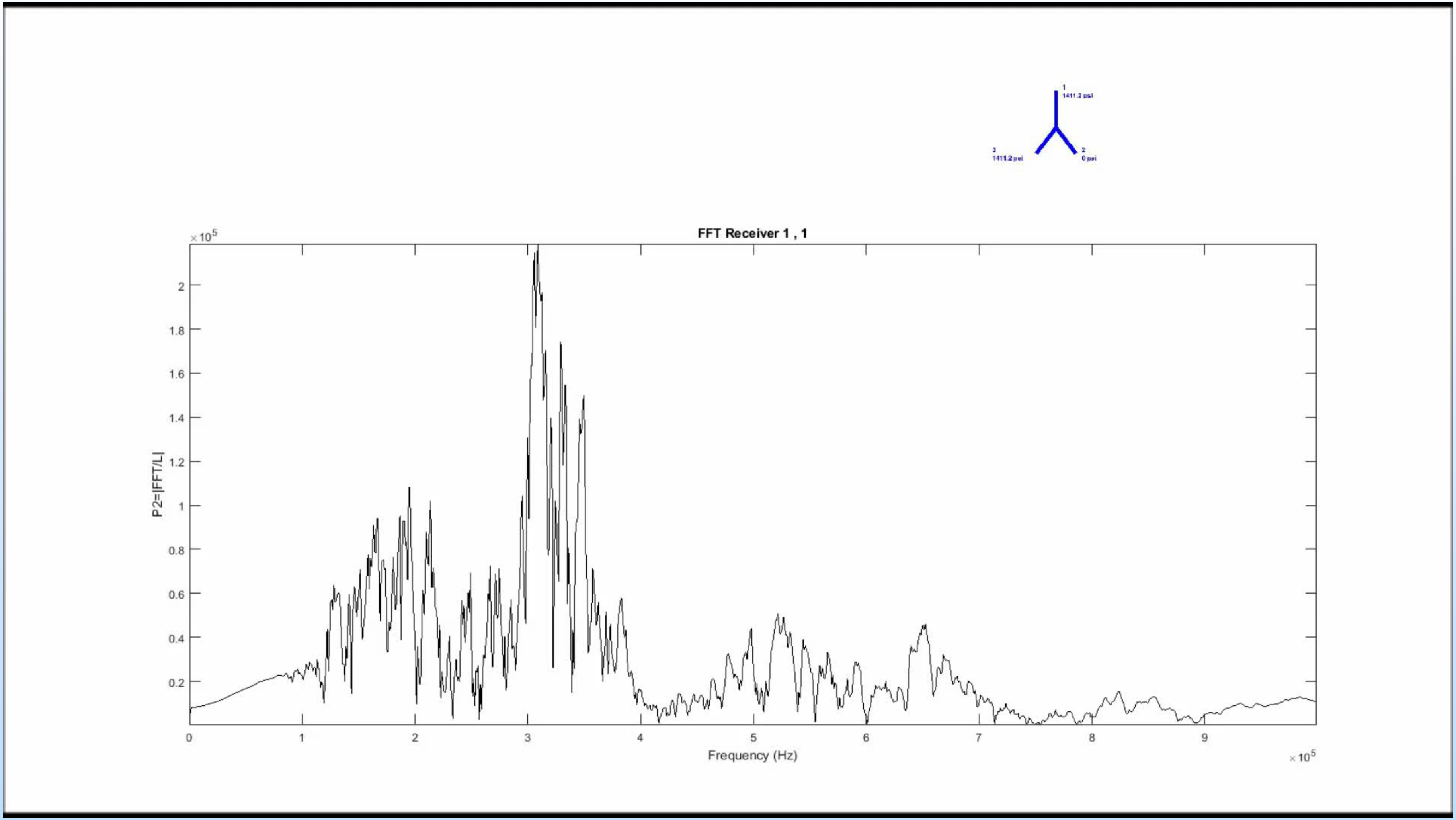




Example Recorded Wave Signal vs Time Variable Load



Example Recorded Wave Signal vs Frequency Variable Load



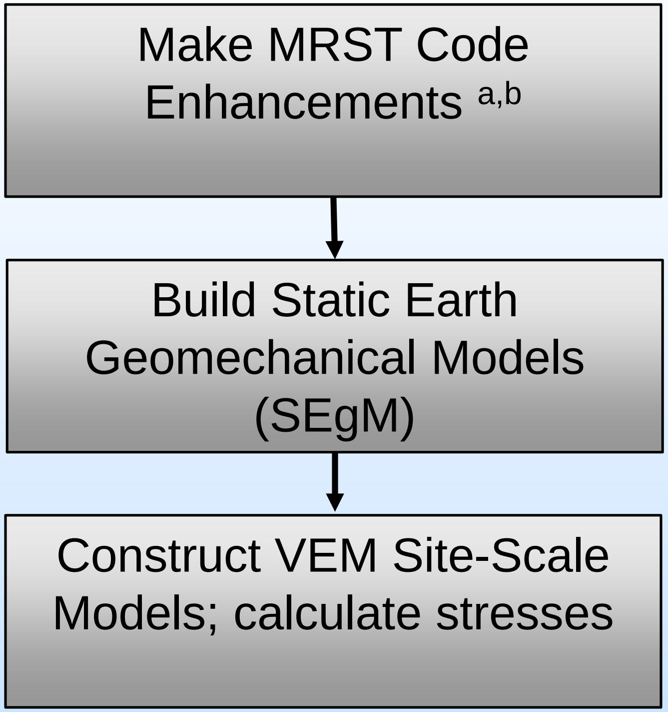
Task 5 – Stress Modeling

- Goal – Build a 3D model of the stress field of an "area" that encompasses each of the two test sites and that is calibrated to the seismic/laboratory derived stress data
  - *i.e., the model is the tool to extend the stress map created from seismic (Task 2) and laboratory (Task 3) approach*

➢ a. add linearr/nonlinear constitutive models for stress/strain relationships

➢ b.**Develop nonlinear optimization to compute the best 3D stress field estimate

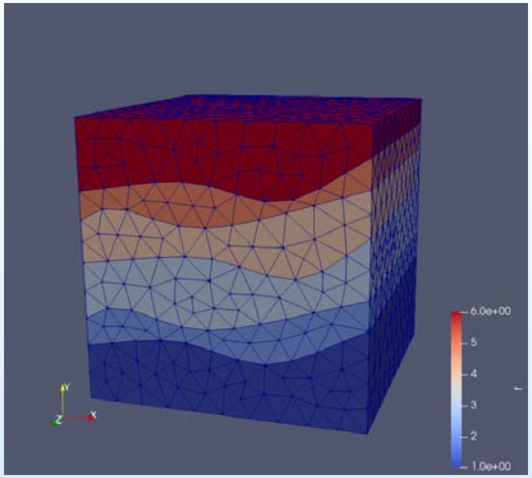
** Novel (new or expanded capability)



This task is being conducted by SINTEF (task lead is Dr. Odd Anderson) and Battelle

Status/Accomplishments – Task 5

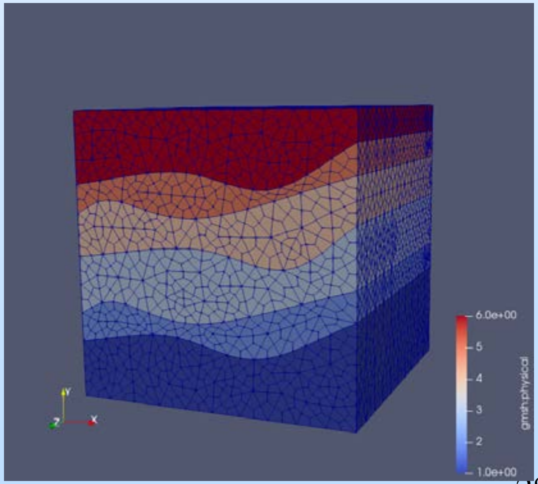
- Initiated development of static earth (site) model for FutureGen2 site (building on model developed by PNNL)
- Completed proof-of concept of the parameter optimization approach on simple, synthetic grids.
- Completed theoretical work to improve the virtual element method (VEM) results on high aspect-ratio grids (geomodel)
- Completed initial work on gradient computations in the geomechanics code in MRST (needed by the optimization engine)



**Proof-of concept work has been promising

On simple synthetic test cases (top figure), correct parameters could be identified with high precision and robustness using finite elements method (FEM)

Next step would be to test on more complex, realistic geomodel grids using virtual element method (VEM)



Project Summary – BP1

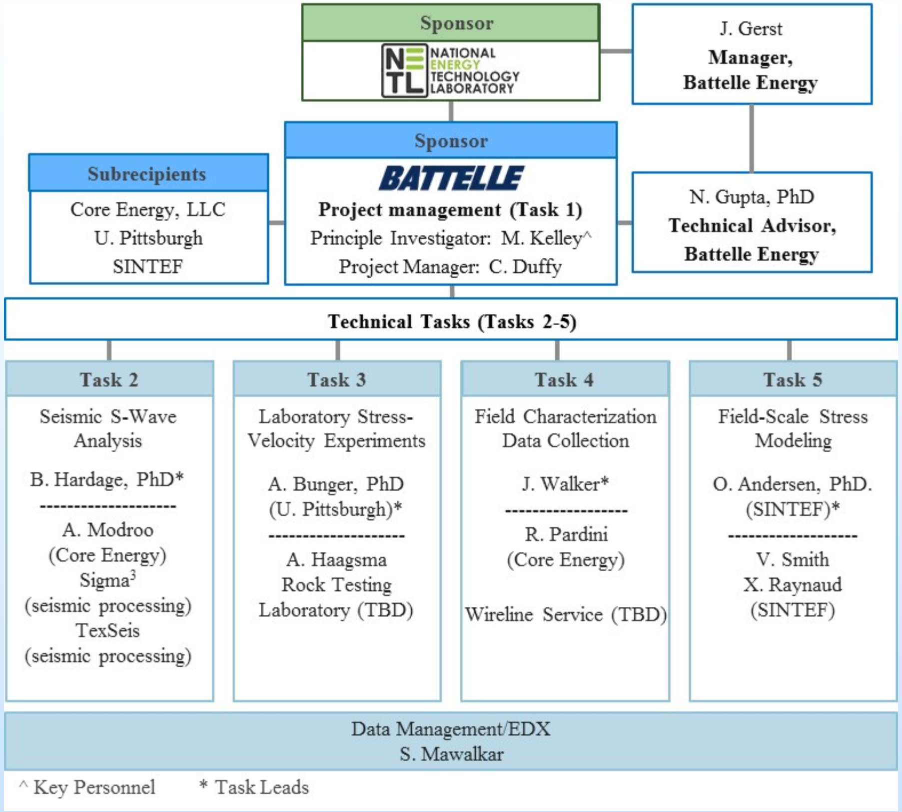
- **Key Findings**.
- It is possible to derive accurate stress orientation from (conventional) seismic data
- Measurements of Shmin in the Michigan test well are consistent with stress measurements by Haimson for deeper formations.
- SucCessFully instrumented miniature rock samples and recorded acoustic waves under varying loading

- **Next Steps**
- Move toward extracting velocity data from Futuregen seismic data
- Finish processing Michigan seismic data for Sfast and Sslow
- Initiate laboratory testing on test site rock samples
- Develop static earth models to allow site stress modeling to begin

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Organization Chart



Schedule and Milestones

Oct 1 2018 — BP-1 (2019) — BP-2 (2020) — BP-3 (2021)

	Quarter (3-month period) after award (assume Oct. 1, 2018)	1	2	3	4	5	6	7	8	9	10	11	12
1.0	**Project Management**												
1.1	PMP,TMP, DMP Updates, EDX[a] Submittals	①											①
1.2	Project Mgmt/Oversight; EV Tracking; Qrtrly Prgrss Rprtng												
1.3	Kick-Off and Annual DOE Briefings												
2.0	**Seismic Data Analysis for Stress Orientation**												
2.1	Acquire/QA Existing Seismic Data												
2.2	Process/Interpret Seismic Data												
2.3	Task 2 Report								③				
MS	Milestone #2: Reprocessing VSP				MS2								
MS	Milestone #3: Reprocessing 3D						MS3						
DP	**Decision Point #1**								DP1				
3.0	**Core Experiments/Testing**												
3.1	Routine Rock Mechanics												
3.2	Triax Ultrasonic Vel Experiments												
3.3	Task 3 Report								④				
MS	Milestone #4: TUV Experiments								MS4				
DP	**Decision Point #2**								DP2				
4.0	**Field Data Acquisition**												
4.1	Task 4 Report				②								
MS	Milestone #1: Field Data Collection				MS1								
5.0	**Site-Scale Stress distribution Modeling**												
5.1	Static earth geomech model development												
5.2	Code Enhancement												
5.3	VEM SITE-SCALE MODELING												
5.4	Model calibration with optimization												
5.5	Task 5 Report												⑤
MS	Milestone #5: VEM Model Calibration										MS5		

a. EDX submittal is due no later than 90 days after completion of the project period and/or as requested by the Project Officer

b. ④ Deliverable

3 one year budget periods, 5 milestones, 8 deliverables, 2 decision points

Deliverables

Task	Deliverable Title	Anticipated Delivery Date
1	Project Management Plan	Update due 30 days after award. Revisions to the PMP shall be submitted as requested by the Project Officer.
1	Technology Maturation Plan	Update due 90 days after award. Revisions to the TMP shall be submitted as requested by the Project Officer.
1	Data Management Plan	Revisions to the DMP shall be submitted as requested by the Project Officer.
1	Data Submitted to NETL-EDX[a]	90 days after completion of the project period and/or as requested by the Project Officer
2	Task 2 Technical Report	end of BP-2 (i.e., 24 months after project initiation).
3	Task 3 Technical Report	end of BP-2 (i.e., 24 months after project initiation).
4	Task 4 Technical Report	end of BP-1 (i.e., 12 months after project initiation).
5	Task 5 Technical Report	end of BP-3 (i.e., 36 months after project initiation).