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

Project Number (FE0031686)

DOE NETL Project Manager
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Presentation Outline

- Project Overview
- Technical Approach/Scope
- Progress and Current Status
  - Overall
  - Task-by-Task
- Summary
- Remaining Work

Program Overview

Project Performance Dates

- 3-yr period of performance
- Oct 2018 – Sept 2021
- 3 1-yr BPs

Funding

- $2,511,832 total
- $2,009,463 fed
- $502,369 non-fed

Project Participants

- BATTELLE – Mark Kelley, Valerie Smith, Christa Duffy
- CORE ENERGY, LLC – Allen Modroo
- UNIV. PITTSBURGH – Andy Bunger, Navid Zolfaghari
- SINTEF – Odd Andersen
- Bob Hardage, consultant
- TEXSEIS (seismic processing vendor) – Mike Graul, Tim Hall
- STERLING (seismic processing vendor) – Richard VanDok
- Schlumberger (well logging/coring/testing vendor)

Overall Project Objectives
(FOA 1826 Topic Area 2)

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) ***at sites considered for CO_2 sequestration***
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

SUMMARY of PROPOSED METHOD for CHARACTERIZING STRESS DISTRIBUTION

For a site considered for CO_2 sequestration:

1. 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 Vs_{fast} and Vs_{slow} data which indicate orientation of SHmax
2. Estimate the magnitude of stress from seismic-derived velocity data (Vs, Vp, etc.) correlated to stress magnitude through laboratory (triaxial ultrasonic velocity) TUV experiments performed on a library of rock types
3. Extend the areal coverage of the seismic-derived stress results beyond the seismic area using numerical modeling

Project Tasks/Scope

- **TASK 1** – Project Management
- **TASK 2** – Acquire/process seismic data for two field sites and determine distribution of stress azimuth throughout seismic area and extract velocity data for predicting stress magnitude HARDAGE/CORE/STERLING/TEXSEIS
  - Futuregen2.0 site Illinois
  - Michigan Core Energy Site
- **TASK 3** – Conduct laboratory TUV experiments on multiple rock types to determine the relationship between magnitude of in-situ stresses (loading) (SH_{max}/Sh_{min}) and velocity data (Vp/Vs, Vs_{fast}/Vs_{slow}) PITT
- **TASK 4** – Conduct in-situ stress tests in Michigan well to obtain field verification data BATTELLE/CORE/ SCHLUMBERGER
- **TASK 5** (Battelle/SINTEF) – Develop site-specific stress models calibrated to seismic data to predict stress orientation and magnitude beyond the seismic area BATTELLE/SINTEF

Overall Progress

- Milestones to date (3 of 5)
  - √ MS1: collect field verification data Site #2 (Q1)
  - √ MS2: process seismic data Site#1 for azimuth (Q5*)
  - √ MS3: process seismic data Site#2 for azimuth (Q7*)
  - *MS4: complete TUV experiments (Q10*)*
  - *MS5: VEM Model Calibration (Q10)*
- Go/No-Go Decision Points to date (1 of 2)
  - √ DP1: Seismic data can be processed for stress azimuthal data (Q8)
  - *DP2: TUV experiments establish relationship between stress magnitude and velocities (Vs_{fast}/Vs_{slow}) (Q10*)*

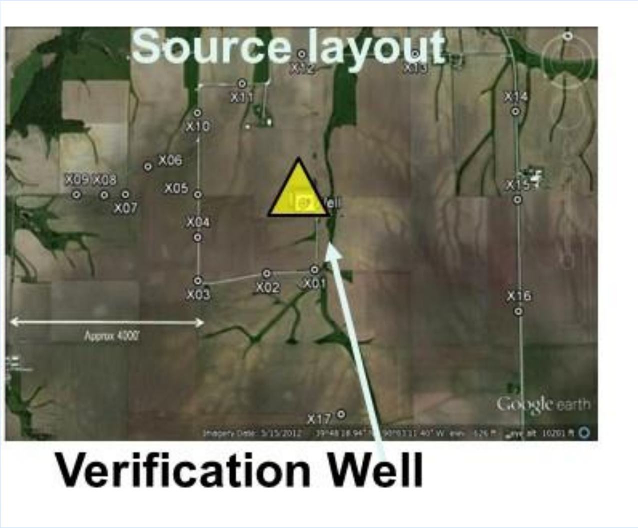
Overall Progress (cont'd)

- Deliverables to date (thru end of Sept) (3 of 5)
  - √ **#1**: PMP,DMP,TMP (Q1)
  - √ **#2**: Report on Task 4 Field Work (Q5)
  - √ **#3**: Report on Task 2 Seismic Processing (Q8)
  - *#4: Report on Task 3 TUV experiments (Q10)*
  - *#5: Report on Task 5 Stress Modeling (Q12)*

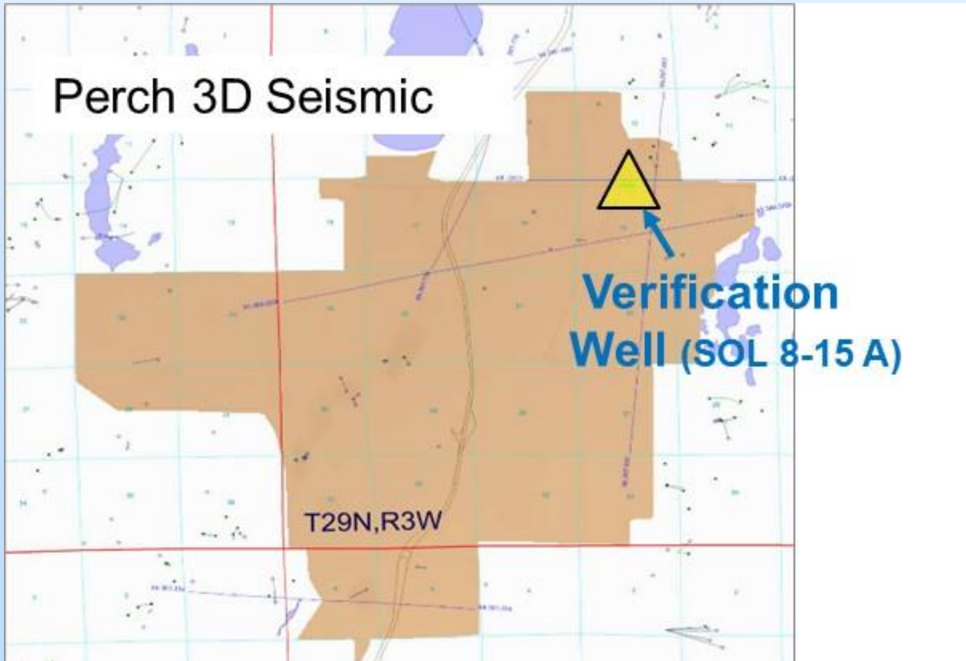
Progress and Current Status (Task 2)

Objectives

- Derive estimates of the azimuth of SHmax horizontal-stress vectors from VSP seismic data acquired from the FUTUREGEN 2 Site (Illinois)
- Derive estimates of the azimuth of SHmax horizontal-stress vectors from traditional, non-invasive, 3D seismic data (Perch 3D Seismic Survey Michigan)
- Verify seismic-derived estimates of stress azimuth against field measurements (e.g., mini-frac tests, sonic-log derived estimates)



FUTUREGEN VSP



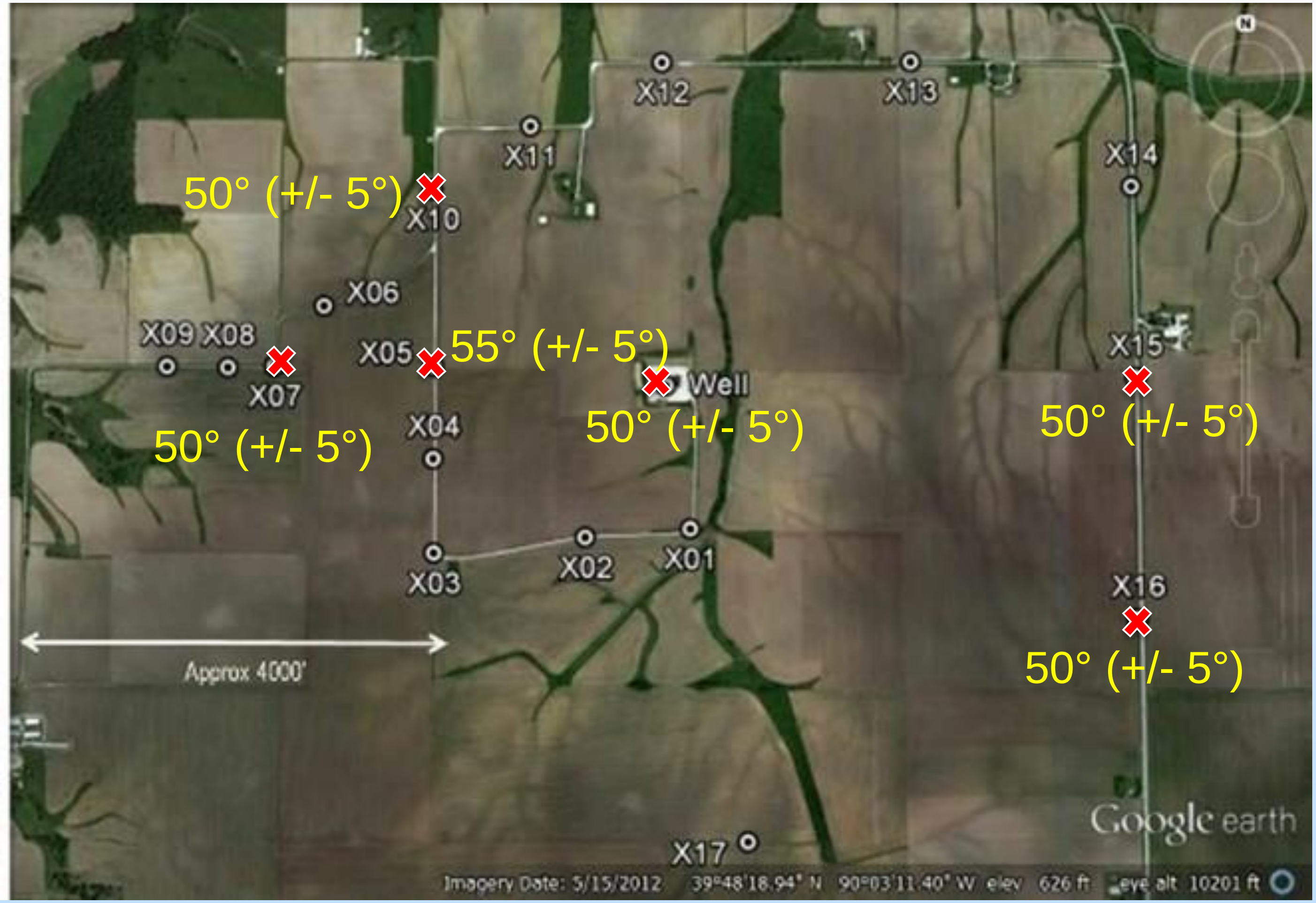
Progress and Current Status (Task 2)

Methodology for Determining Stress Direction from Seismic Data

- In stressed rocks, shear(S)-waves split into fast and slow mode that are polarized orthogonal to each other and that have different propagation velocities
  - SHmax azimuth corresponds to fast S-mode (displacement vector) direction
  - Shmin corresponds to slow S-mode direction
- S-wave seismic sources are uncommon; however, incidental S-wave data generated by conventional seismic (P-wave) sources can be exploited
  - “Sv-P” data are upgoing P waves from downgoing S waves can be recorded by conventional P-wave (vertical) geophones contain the necessary S-wave data for analysis
- In this project
  - vertical (P-wave) vibrators were used to generate the VSP data at the FutureGen site
  - shot-hole explosives were used to generate the 3D seismic data at Michigan site.
- Separate methods were developed to extract S-wave data from VSP and 3D seismic data
  - (VSP) S-wavelet rotation method – *This wavelet-rotation procedure is new, has never been demonstrated before*
  - (3D Seismic) Sv-P trace gathers approach. *This study appears to be the first-ever use of SV-P trace gathers to define Shmax azimuth.*

Progress and Current Status (Task 2)

SHmax Azimuth Determined from the Futuregen VSP Data



SHmax azimuths determined for 6 VSP source locations are remarkably consistent ~50 to 55° (+/-5°)

Seven open-borehole stress tests conducted in the FutureGen2 VSP receiver well (2013):

- N 51± 4°E, in the Mount Simon (3 tests);
- N 63±9°E for 3 tested intervals in the Pre-Cambrian
- N77°E for 2 other tests in the Pre-Cambrian.

FUTUREGEN VSP

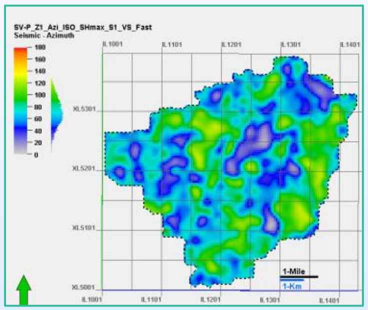
Progress and Current Status (Task 2)

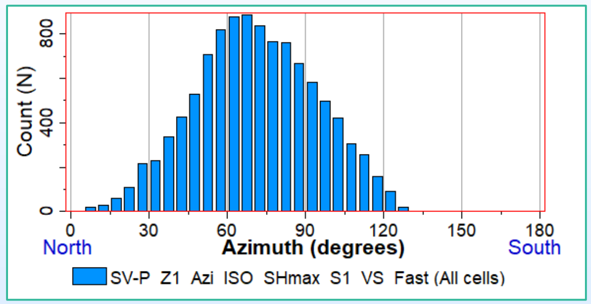
SHmax Azimuth Determined from the Michigan 3D Seismic

Estimates were made from Sv-P data at each 82.5 ft x 82.5 ft stacking bin across the Perch 3D survey for 3 potential CO_2 storage reservoirs: Bass Islands Dol; Brown Niagaran; St. Peter SS

Stress Azimuth Map | Stress Azimuth Histogram

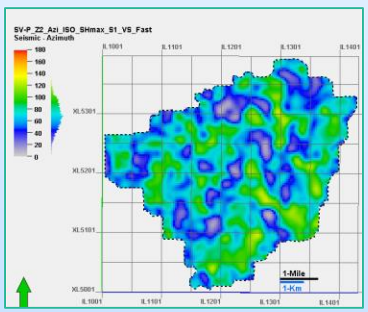
Bass Islands

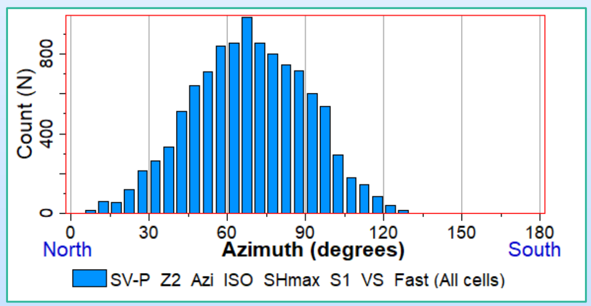




65° (+/- ~ 15°)

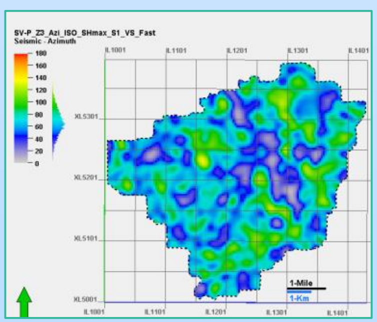
Brown Niagaran

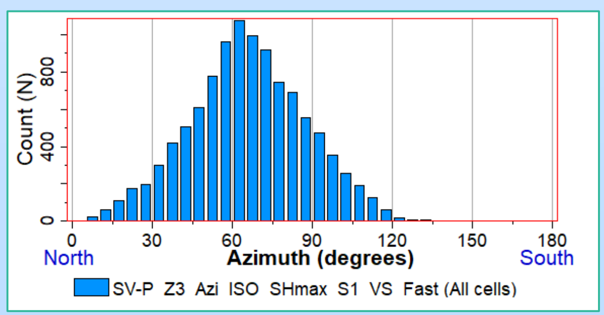




65° (+/- ~ 15°)

St Peter





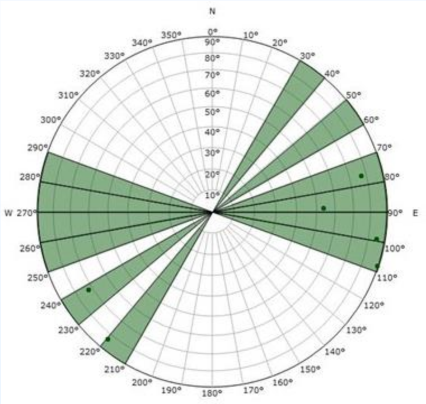
60° (+/- ~15°)

Progress and Current Status (Task 2)

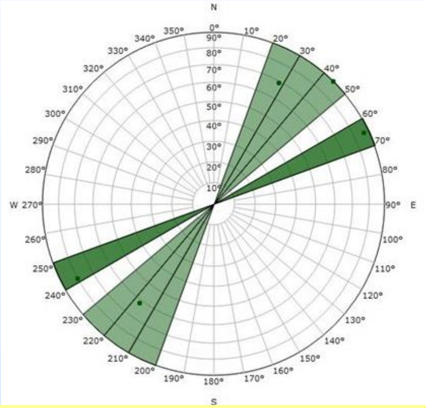
Verification of Shmax Azimuth determined from Seismic Data

Verification Stress Data is available from the SOL-8-15A well in the Perch 3D seismic area

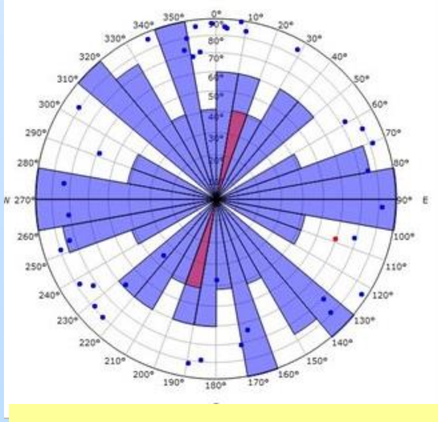
Fractures that are oriented at 65 degrees are probably extensional fractures (which are oriented in SHmax azimuth)
the other fractures are likely shear fractures (which are oriented in directions that are oriented in directions that are approximately 30 degrees away from SHmax azimuth)

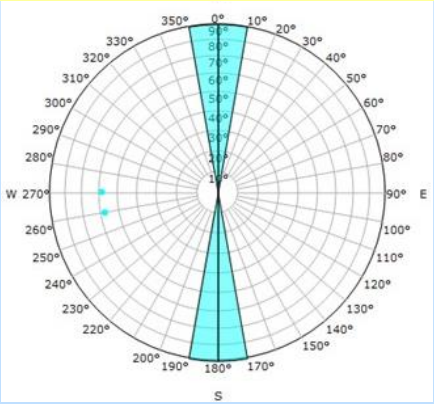


Drilling Induced Fractures
SHmax 30-110°

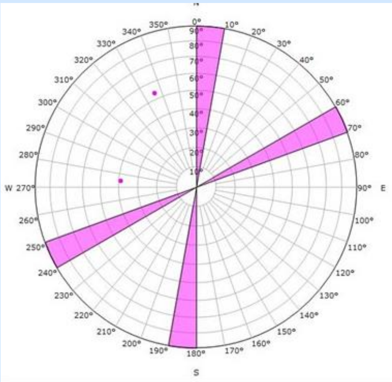


Mini-Frac (Induced) Fractures
SHmax 20-70°





Natural Fractures (conductive – left; resistive – right)



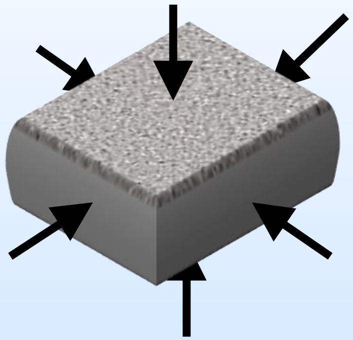
Faults
SHmax 5/65°

Progress and Current Status (Task 3)

Laboratory TUV Experiments

- Goal is to determine relationship between triaxial stress (direction and magnitude) and ultrasonic velocities (Vp, Vs, Vp/Vs, Vs_{fast}, Vs_{slow}).
- 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).

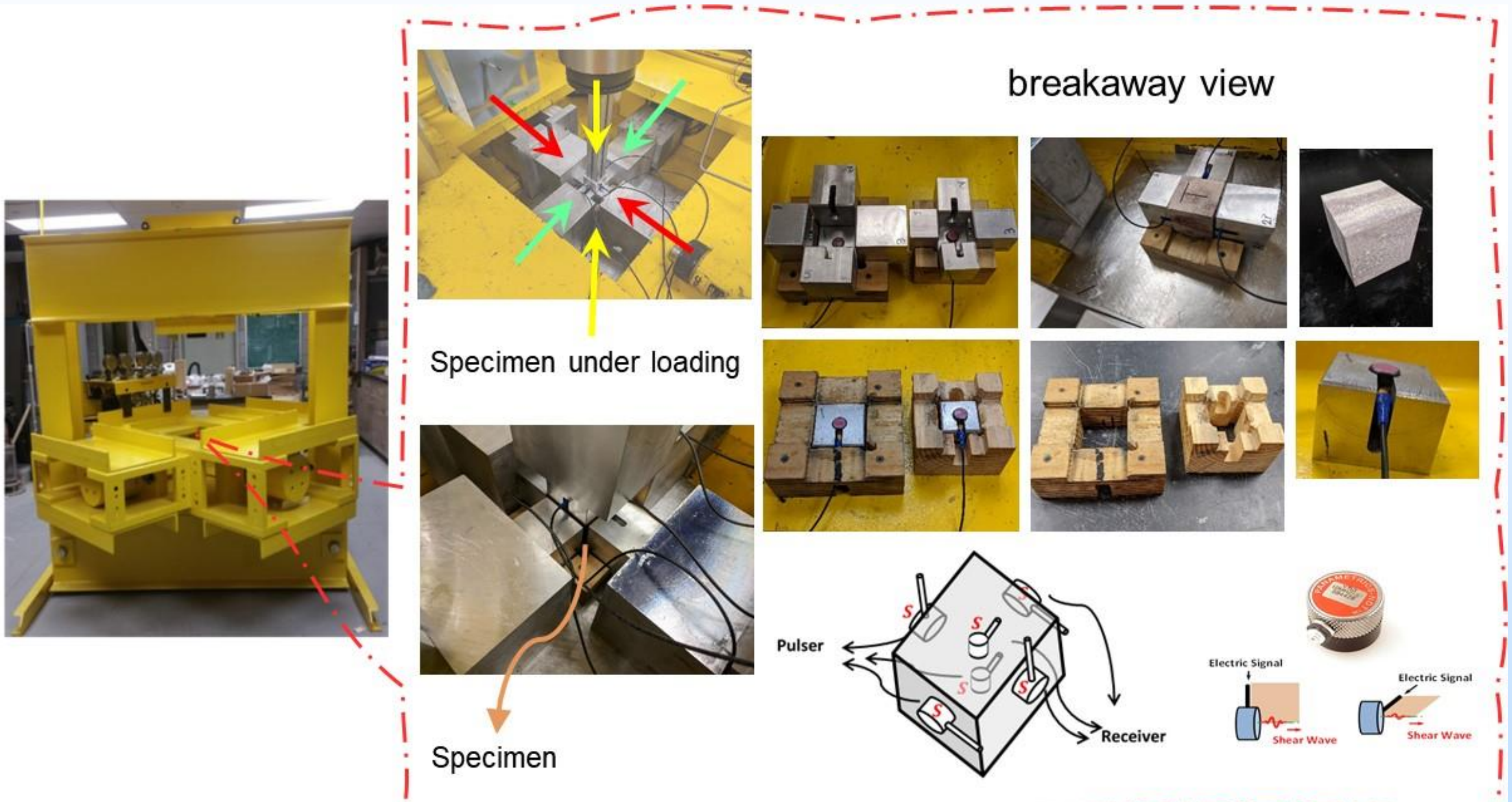
Stress-induced Anisotropy



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

Progress and Current Status (Task 3)

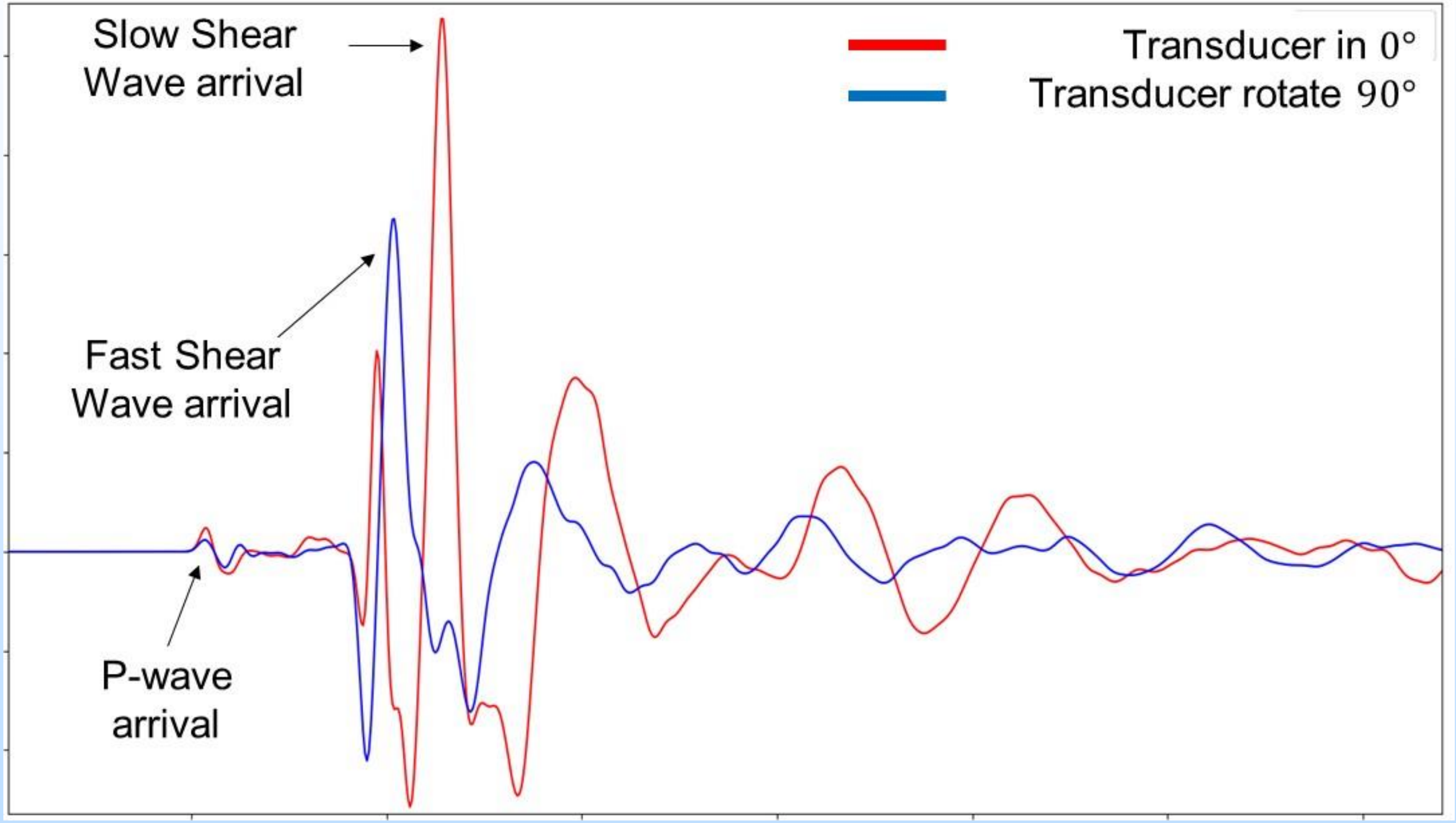
Experimental Setup



– this is true triaxial, which is needed to characterize 3 stress components in field. Past research typically isotropic load or axisymmetric load only

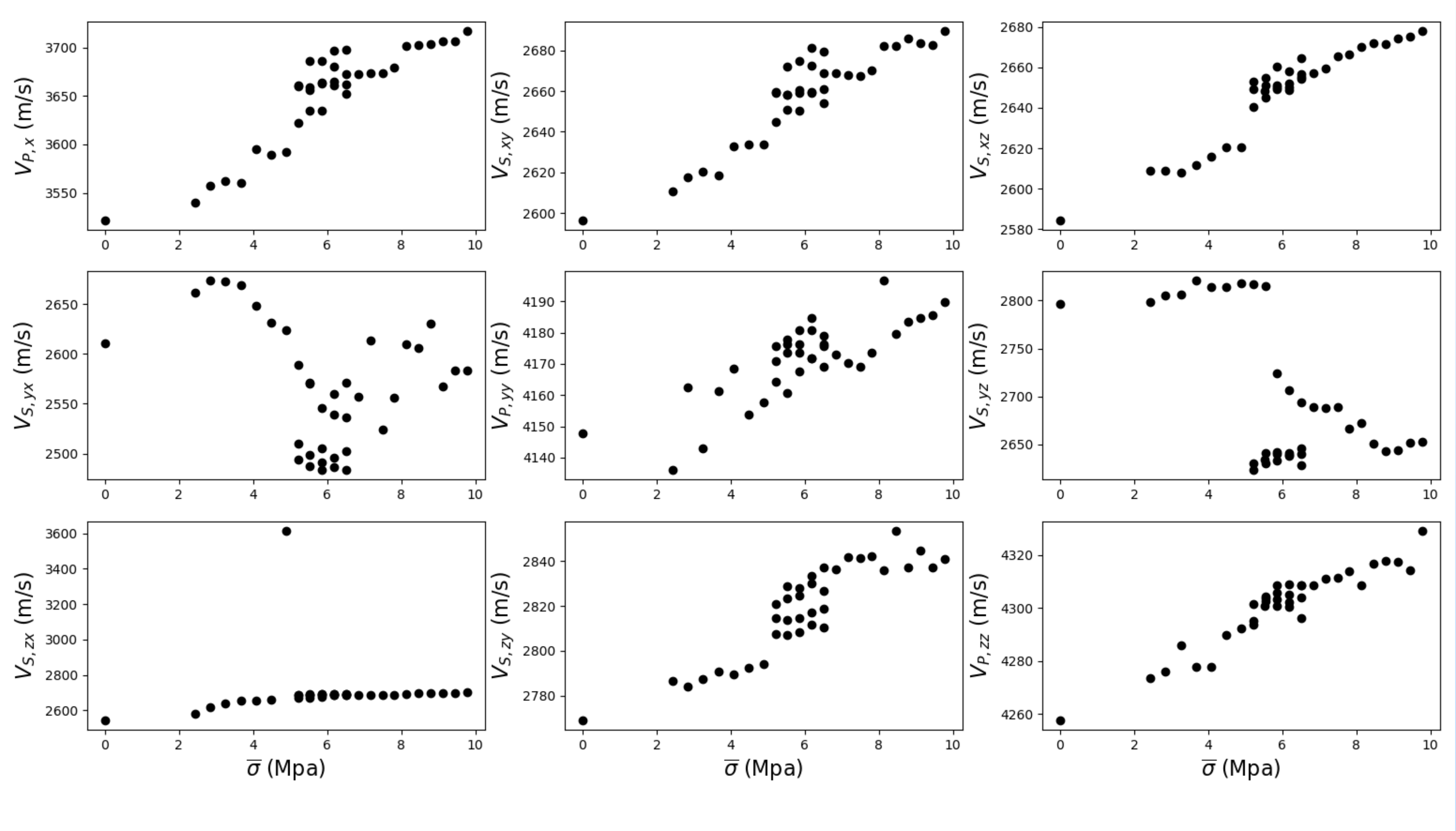
Progress and Current Status (Task 3)

Example Vp, Vs_{fast}, Vs_{Slow} Data



Progress and Current Status (Task 3)

Example Vp, Vs velocity data recorded during 50 loading steps



Progress and Current Status (Task 3)

Data Interpretation

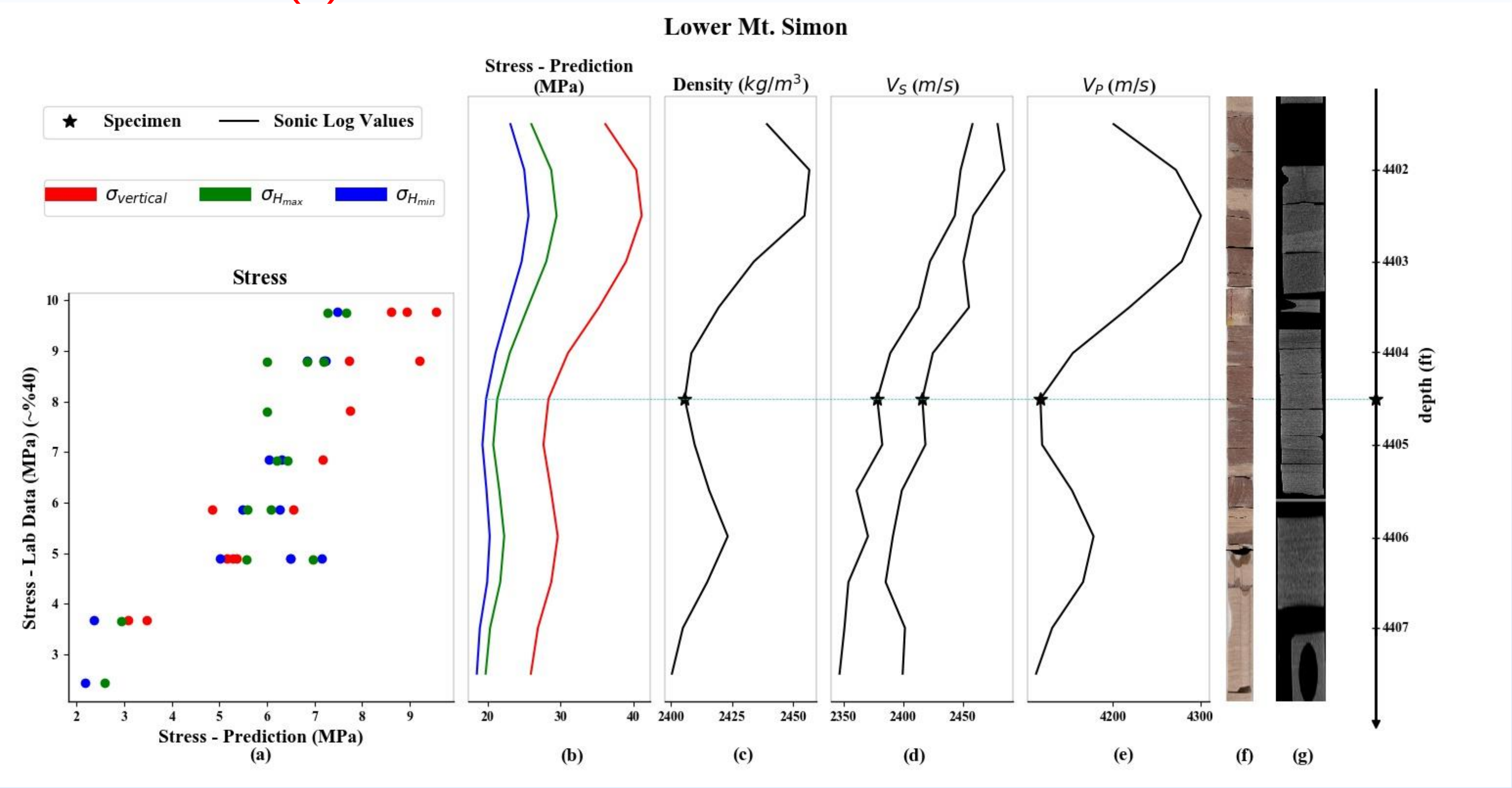
Goal was to develop method to for estimating stress magnitude from seismic velocity data and laboratory-defined relationship between loading (stress magnitude) and velocities (Vs, Vp)

- A linear regression method based on acousto-elasticity theory was developed but did not work out
- *A* method based on ***Machine Learning*** was developed that seems promising
  - Train a machine learning (ML) algorithm on the laboratory data, resulting in an ML based method for estimating stresses magnitude given measured wavespeeds (and vice versa).
  - Deploy the ML model on the wavespeeds obtained from open hole, multipole sonic log of the formation(s) of interest (rather than velocity data from seismic survey)

Progress and Current Status (Task 3)

Demonstration of machine learning (ML) method for estimating stress using Lower Mt. Simon formation from the FutureGen exploration well, Illinois.

(a) (b) (c) (d) (e) (f,g)

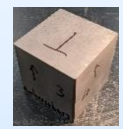


- (★) One sample extracted at depth 4404.5 ft and tested under various tri-axial loadings.
- (a) Train the ML model using 60% of lab data and test with 40% remaining.
- (c-e) Using Sonic Log values as input to the ML model.
- (b) ML Estimate of all three in-situ stresses.
- (f,g) core photo and CT scan

Progress and Current Status (Task 3)

Summary of Work Completed to Date

Analyze	Data Extraction	Experiment	Sample	FutureGen
	✓	✓		Eau Claire
	✓	✓		Upper Mt Simon
	✓	✓		Lower Mt Simon
✓	✓	✓		Precambrian

Michigan Core	Sample	Experiment	Data Extraction	Analyze
Amherstburg		✓	✓	
Dundee		✓	✓	
Niagara Reef		✓	✓	

All TUV tests completed on 4 Futuregen samples and 3 Michigan samples

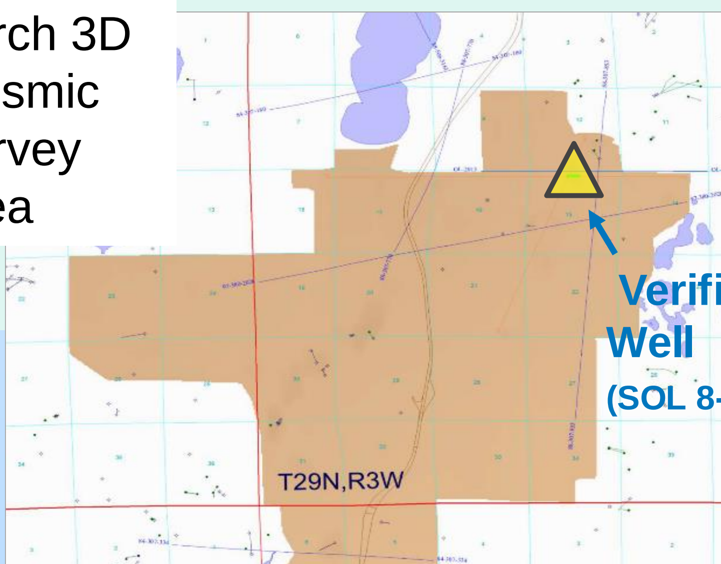
Progress and Current Status

Task 4 – Well Logging/Testing

Goal was to obtain stress measurements from the SOL8-15A well to verify stresses derived from seismic data and collect data to support model

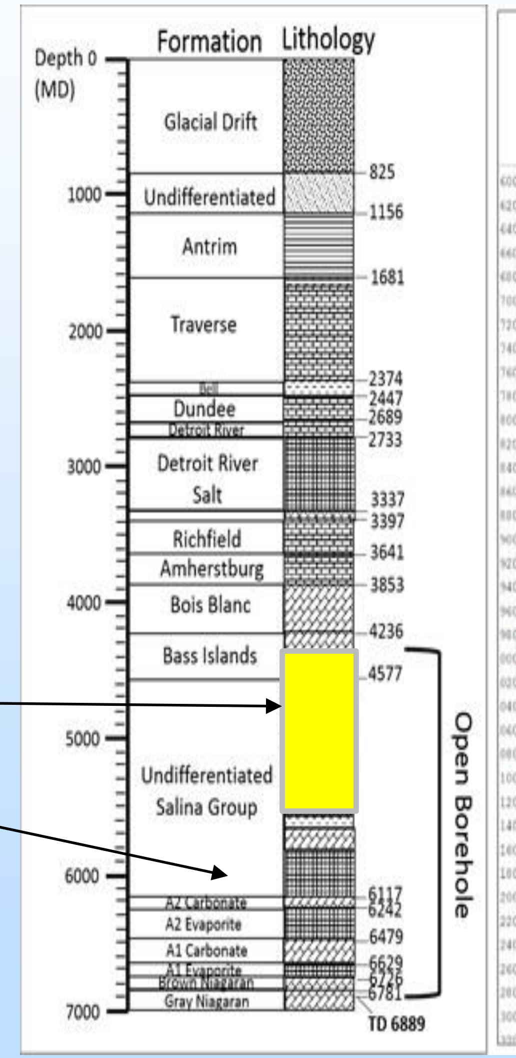
- Field Work Completed July/Aug 2019
- 3 mini-frac tests provide stress orientation (Sh_{min} and SH_{MAX} (orientation) and magnitude (Shmin)
- Sonic log data provide SH_{MAX} (orientation)
- Sonic log data provide rock mechanical properties

Perch 3D Seismic Survey Area

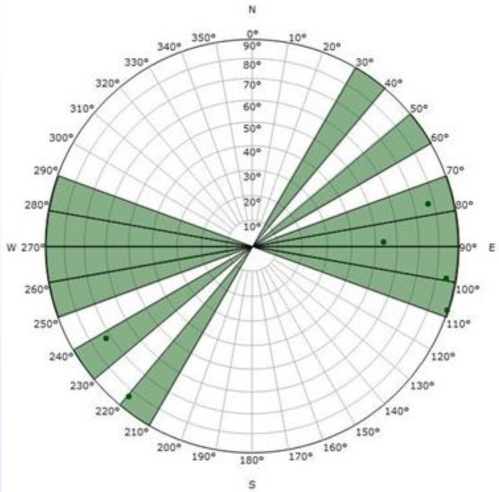


Test interval was 4296 to 5300 ft

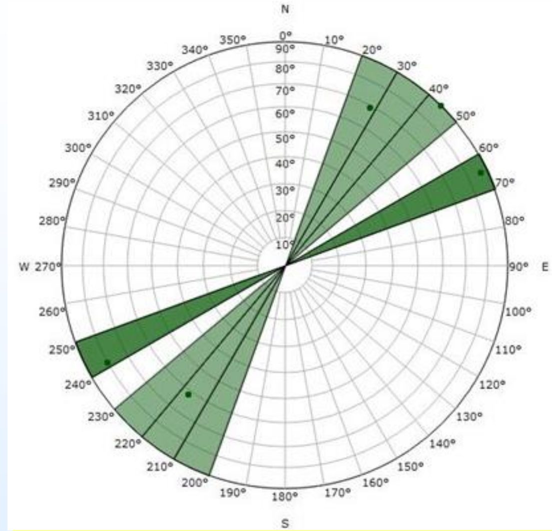
Borehole was not accessible below 5300 ft.



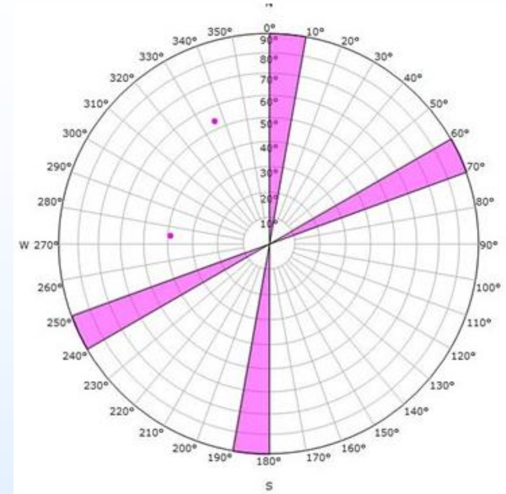
Stress Orientation Data from Sonic Log and Mini-frac Tests



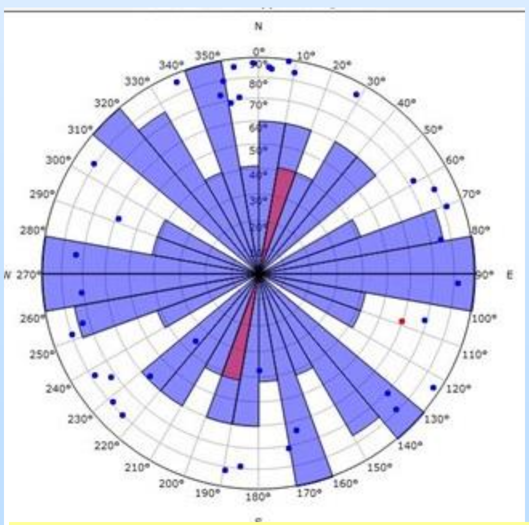
Drilling Induced Fractures
Shmax 30-110°

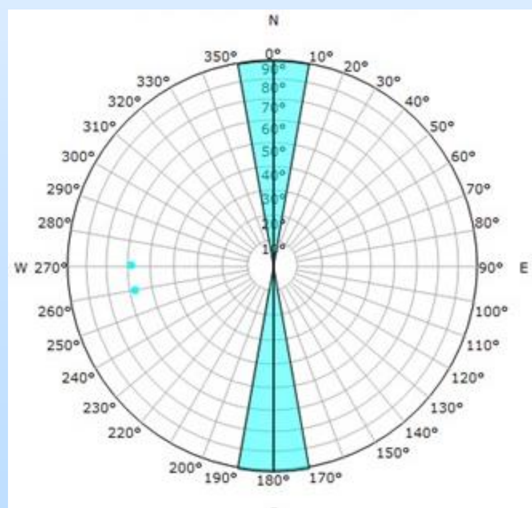


Mini-Frac Induced Fractures
Shmax 20-70°



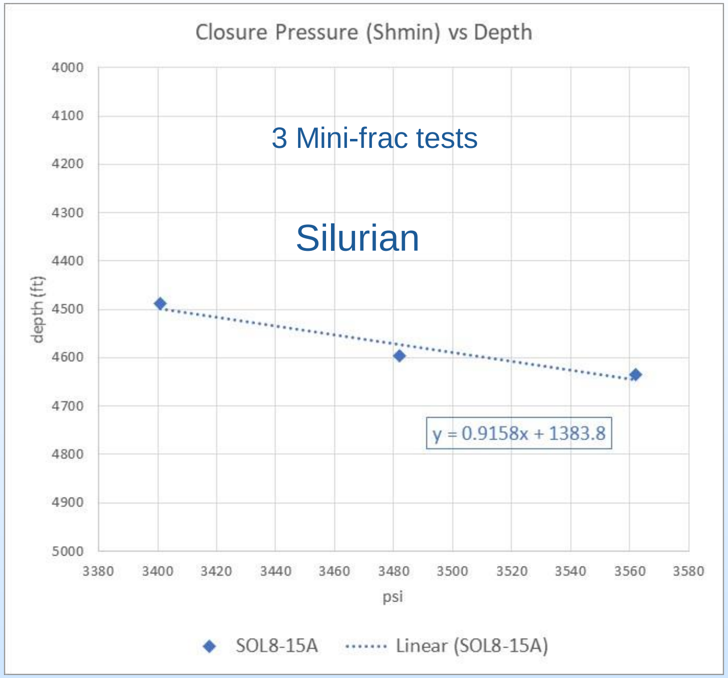
Faults
Shmax 5/85°



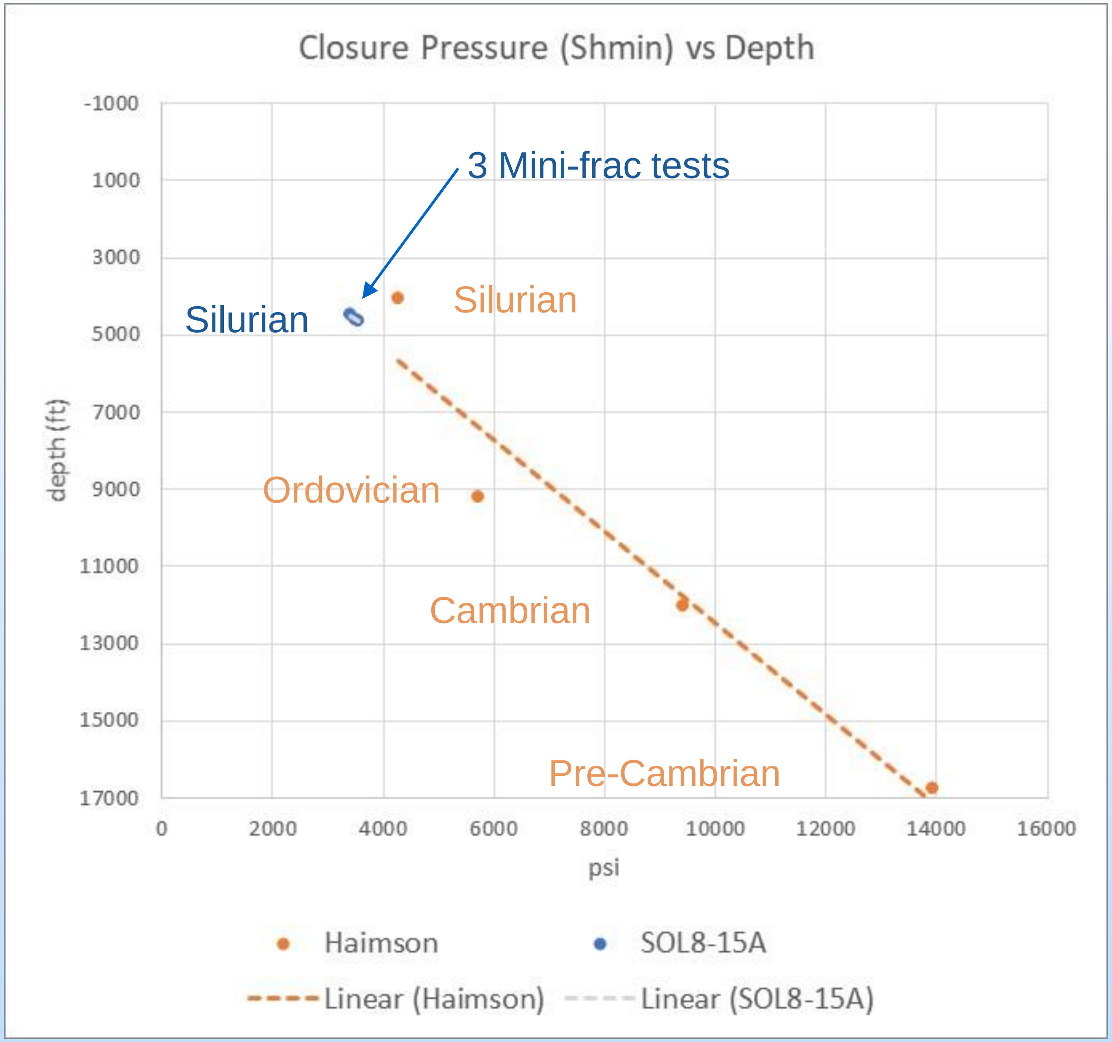


Natural Fractures (conductive – left; resistive – right)

Stress Magnitude (Sh_{min}) from Mini-Frac Tests Consistent with Haimson Data



Shmin magnitude: 0.76 to 0.77 psi/ft



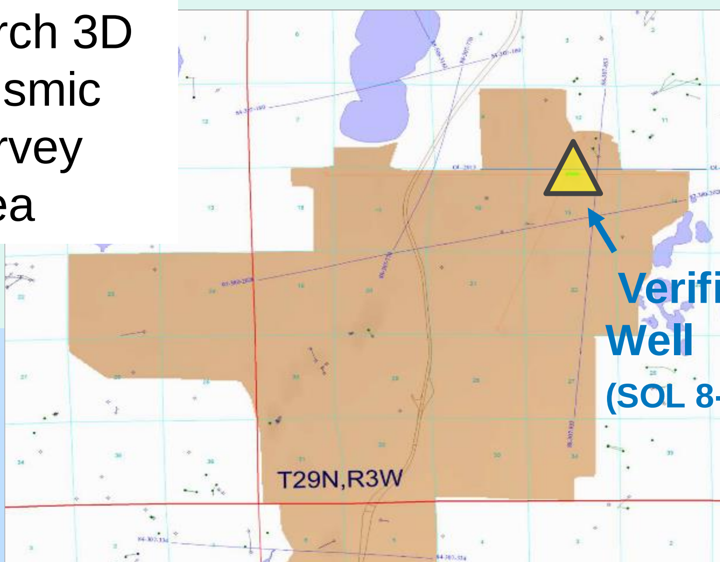
Progress and Current Status

Task 4 – Well Logging/Testing

Goal was to obtain stress measurements from the open borehole section of the SOL8-15A well to verify stresses derived from seismic data and collect data to support Tasl 5 stress model

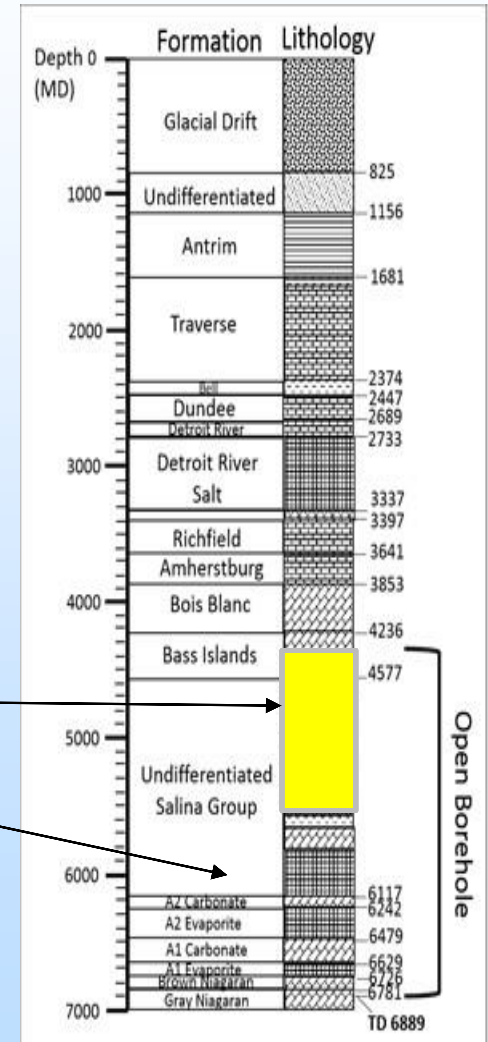
- Field Work Completed July/Aug 2019
- 3 mini-frac tests provide stress orientation (Sh_{min} and SH_{MAX} (orientation) and magnitude (Shmin)
- Sonic log data provide SH_{MAX} (orientation)
- Sonic log data provide rock mechanical properties

Perch 3D Seismic Survey Area



Test interval was 4296 to 5300 ft

Borehole was not accessible below 5300 ft.



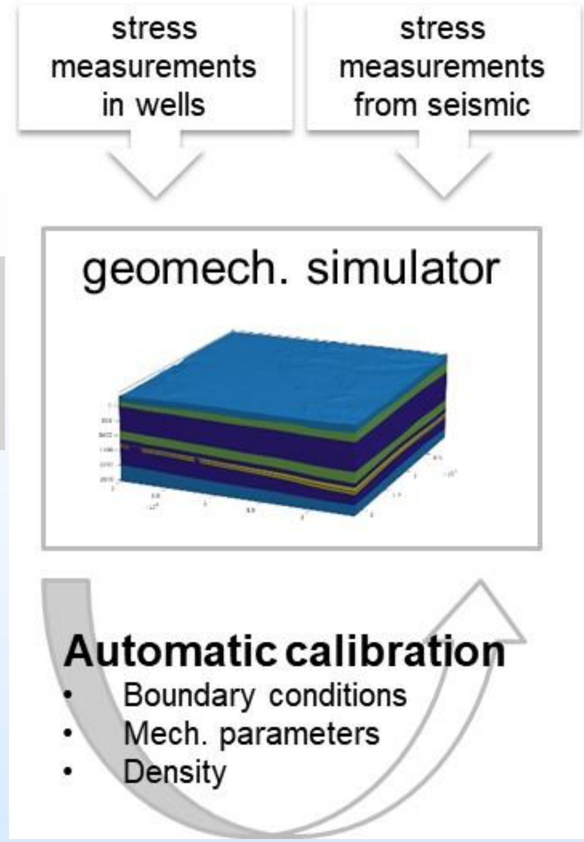
Progress and Current Status

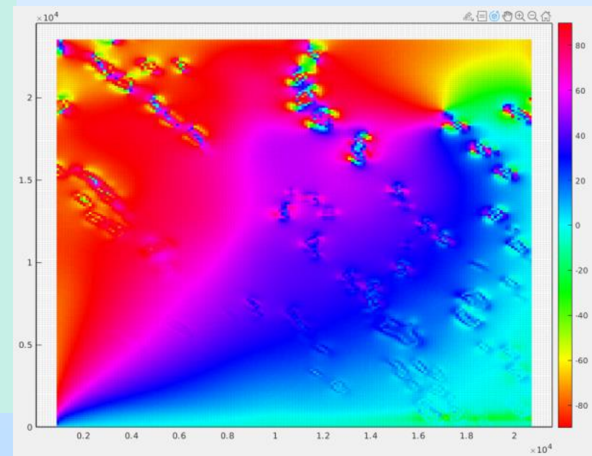
Task 5 – Site Scale Stress Modeling

Goal is to develop calibrated site-scale stress model for each of the two verification sites; use the models to estimate stress beyond the seismic survey area

Progress:

- Constructed 3D Static Earth Model in PETREL software of each site to define geologic framework and assimilate rock and fluid properties
  - Both models extend from land surface to pre-Cambrian basement rock
- Imported SEM model into MRST code; constructed 3D dynamic geomechanical model; initial stress simulations completed
- Developed prototype non-linear optimization (automatic calibration) code/routine
- Currently working on implementing calibration process





Simulated principal stress direction at Perch site Brown Niagaran Formation
<u>Uncalibrated, for illustrational purpose only</u>

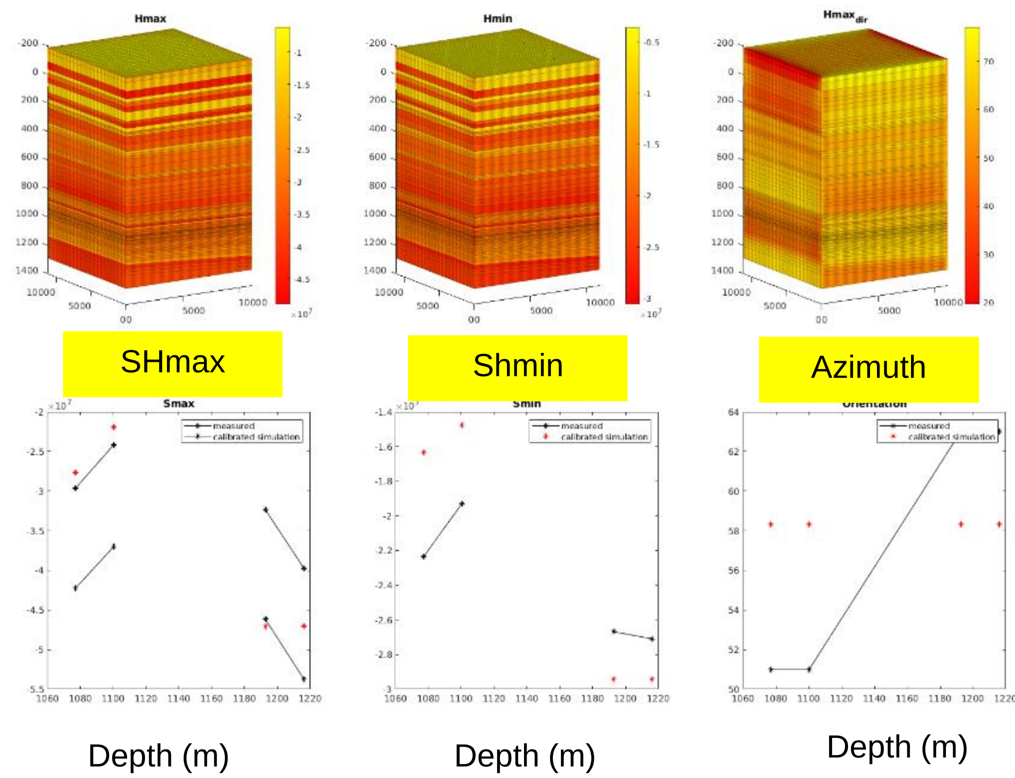
Progress and Current Status

Task 5 – Site Scale Stress Modeling

Initial prototype automatic model calibration with optimization implemented for FutureGen model:

- Material density
- Elastic moduli
- Boundary conditions

- Preliminary testing confirms automatic calibration confirms it works as expected.
- Result from calibration should gradually improve with more data
- Remaining - full parameter calibration procedure applied to FutureGen and Perch models



Automatic calibration of layer-wise material properties to point-wise measurement data, here carried out on a simplified version of the FutureGen model.

Summary Slide

- Completed logging/in-situ stress testing in SOL8-15A well to provide data to verify non-invasive test method (Michigan test site)
- Demonstrated S-wave rotation method for determining stress orientation from VSP seismic data (Illinois site)
- Demonstrated Sv-P trace gather method for determining stress orientation from 3D seismic data (Michigan site)
- Completed TUV experiments on 7 rock samples to quantify relationship between stress magnitude/ direction and Vp/Vs, Vs_fast, Vs_slow

Summary Slide (cont'd)

- Thus far have not been able to apply TUV data to seismic (velocity) data to predict stress magnitude in non-invasive manner
- Developed ML method for predicting stress magnitude from Laboratory TUV data and open-hole sonic log velocity data (not strictly non-invasive)
- Constructed site-scale geomechanical model for Illinois and Michigan test sites; completed initial stress simulations
- Developed non-linear optimization (automatic calibration) code/routine; completed initial testing

Future Work (FY21)

- Site-scale stress modeling (Task 5) – apply full parameter calibration procedure to FutureGen and Michigan models; complete work on constitutive models
- (Task 3) Continue to work on data interpretation method to link TUV data to seismic velocity data to predict stress magnitude
- Complete task reports (Tasks 3, 5)
- Prepare manuscripts for journal publication
  - Seismic methods
  - TUV experiments
  - Stress modeling
  - SPE RSC 2021 (submitted) - "Automatic calibration of geomechanical models from sparse data for estimating stress in deep geological formations"