Identification of Faults Susceptible to Induced Seismicity

Project Number DE-FE0031685

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U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

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Project Participants

- Geologic and geocellular modeling
  - James Damico, Mansour Khosravi ISGS
- Fault identification
  - Hongkyu Yoon (Sandia) machine learning
  - Michael Fehler (MIT) inversion modeling
- Pressure and stress perturbation modeling
  - Ruben Juanes (MIT)
  - Scott Frailey (ISGS)
- Stress field modeling
  - Ahmed Elbana (UIUC)

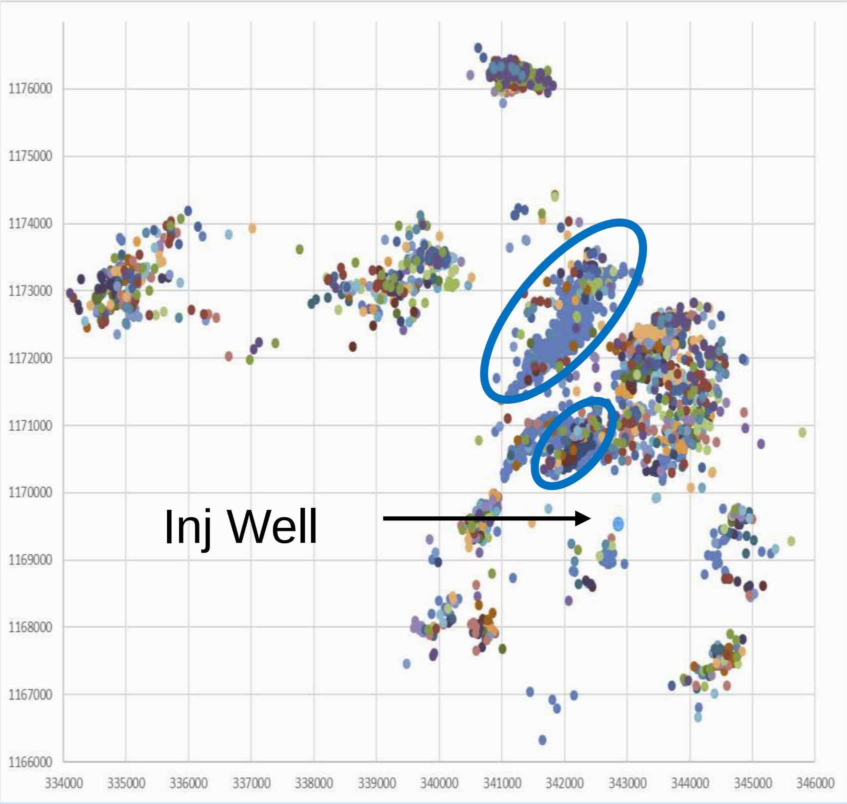
Presentation Outline

- Motivation, Objective, and Approach
- Technical Status
  - Expected Outcomes
  - Workflow
  - By Task
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary

Motivation

- At a “quiet” seismic area, microseismic events recorded and attributed to CO_2 injection at relatively low injection pressure
  - <10 events in 1.5 yrs pre-injection monitoring
  - Pressure
    - Injection 15% above Pi;
    - @1000 ft 5% above Pi
  - 4700+ located events
  - Located primarily in the crystalline basement rock

IBDP Site after 3 yrs injection



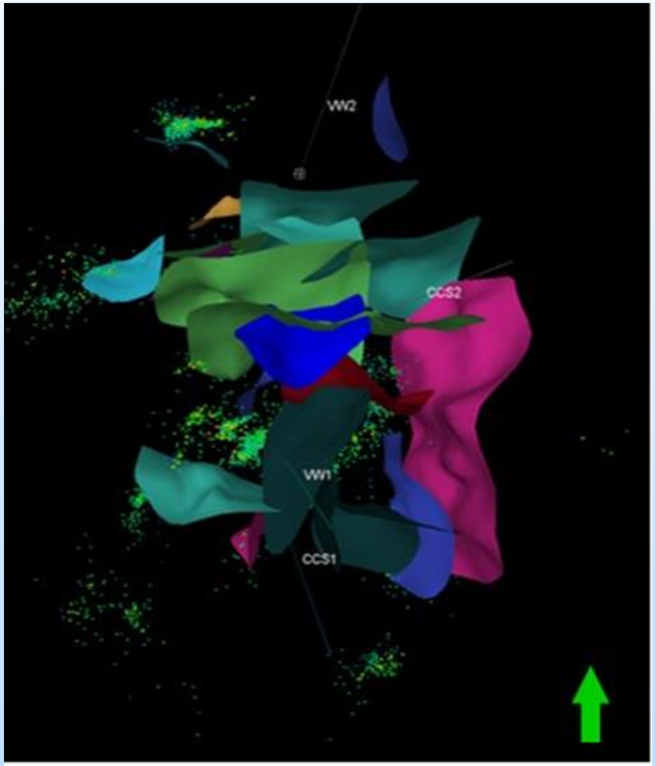
After R. Bauer, ISGS

1000 x 1000 ft squares

Objective

- Predict presence of faults susceptible to movement from fluid injection
  - identify characteristics of these faults
  - estimate in-situ stress field changes before and after fault slippage
  - explain pressure and stress perturbations between the storage unit and crystalline basement (vertical migration)

Fault Locations from Traditional Methods (Surface Seismic)



S. Williams-Stroud, H. Leetaru, 2020

Approach

- Test a series of geologically based, integrated forward and physics-constrained, data-driven (inverse) models that includes the following:
  - geocellular models of a well-characterized field site with microseismicity located within basement rock,
  - machine learning to better resolve basement faults unidentifiable via traditional surface seismic methods
  - poroelastic modeling to understand pressure and stress fields in the presence of characterized faults,
  - seismic modeling to determine geologic/petrophysical properties of crystalline basement rock, faults, and overlying storage units that control seismicity

Technical Status: Expected Outcomes

- Advance knowledge of the transmission of pressure and stress between the storage unit and underlying crystalline basements
- Establish workflow that can identify the presence of faults that are susceptible to induced seismicity in the presence of CO_2 injection
- Compare results with traditional means of identifying faults (e.g. surface seismic)
- Reduce the geomechanical risk component of storage

Technical Status: Workflow Diagram

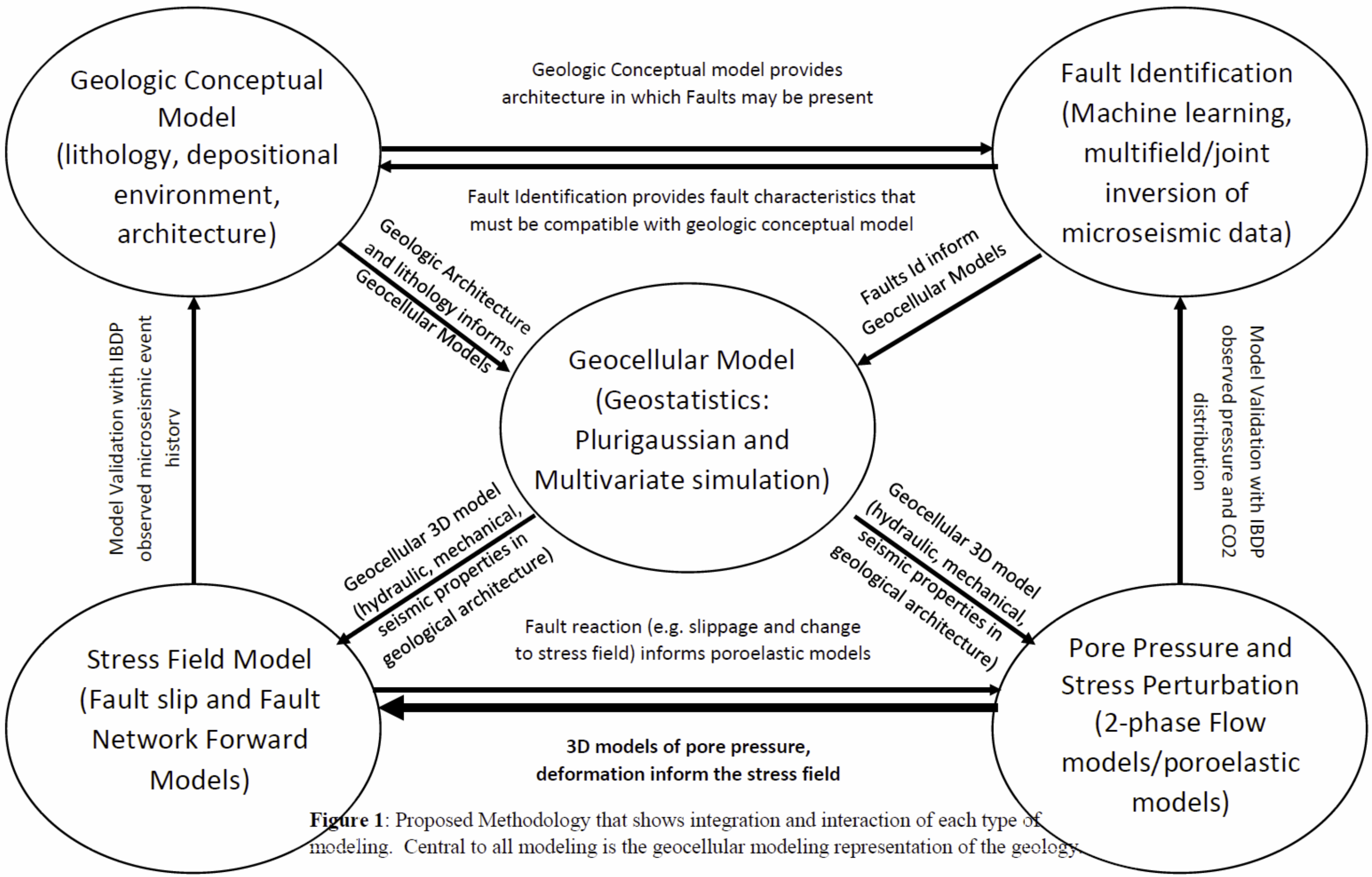
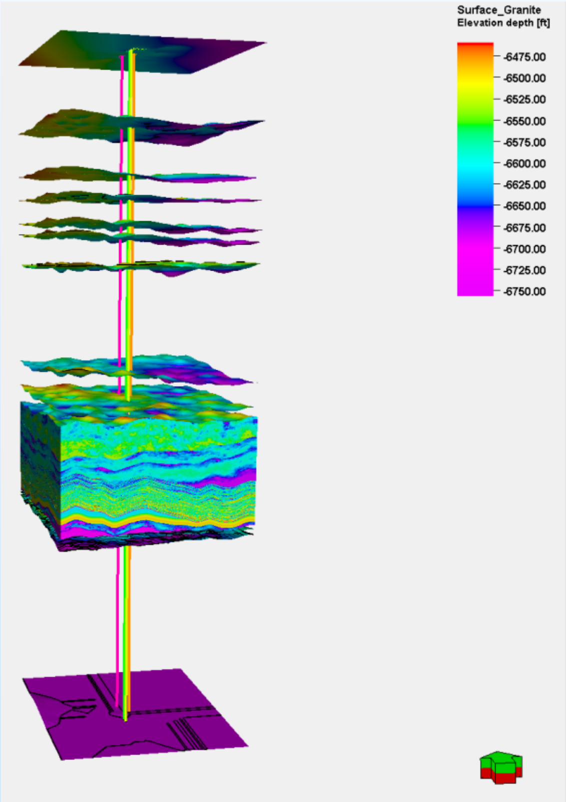


Figure 1: Proposed Methodology that shows integration and interaction of each type of modeling. Central to all modeling is the geocellular modeling representation of the geology.

Technical Status: Task 2
Conceptual Geologic Modeling

- Enhance existing models of field site geology, including faults
- Reconfigure existing grids and formats for dynamic simulations
- Enhance model with stratigraphic and structural features of overlying/underlying strata
- Distribute petrophysical and geomechanical properties based on conceptual geologic model
- Update model with faults from Task 3: Fault Identification

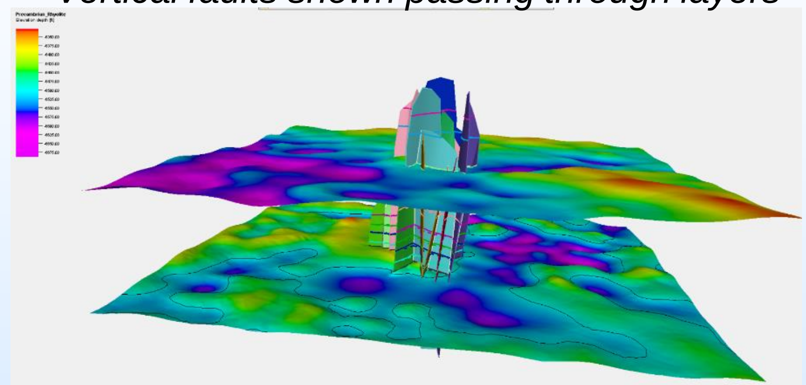
Structural framework of the model from ground surface to base of the Precambrian

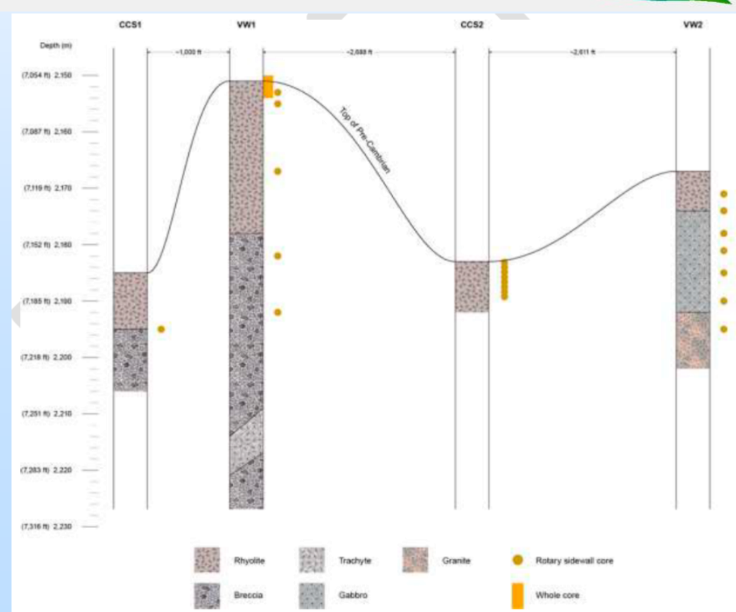


Technical Status: Task 2
Conceptual Geologic Modeling

- Characterized geology of entire "relevant" formations
- Detailed characterization of upper crystalline basement (between injection interval and microseismic sources (locations)
- Finalized initial fault model based on traditional geophysical approaches
- Continuous modification to geologic conceptual and geocellular models to improve model calibration

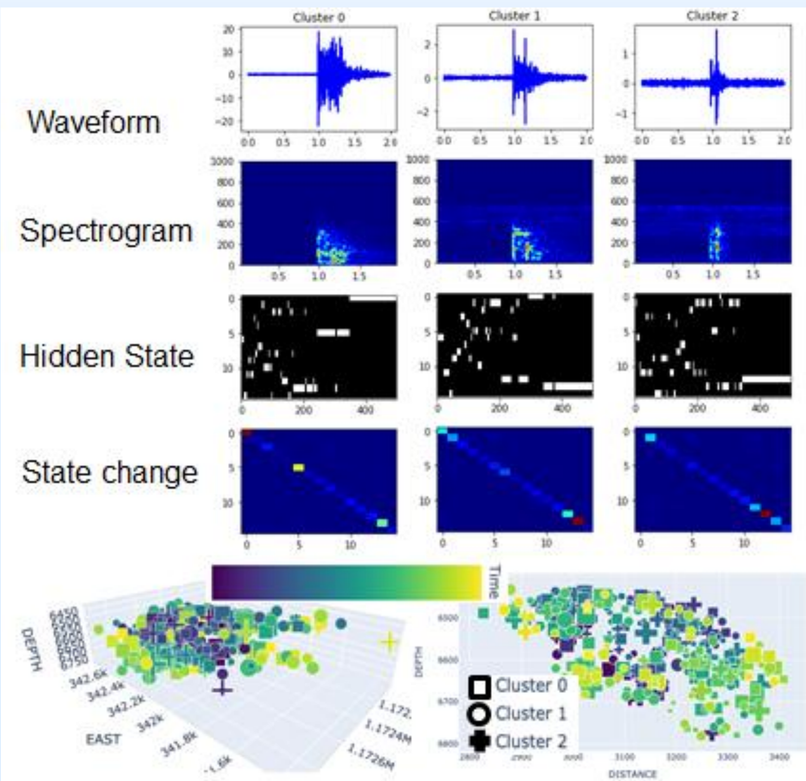
Vertical faults shown passing through layers





Technical Status: Task 3 Machine Learning

- Improve detection of low-magnitude events to discover undetected fault/fracture
- Characterize waveforms' relations among events, identify event locations with forward/inverse modeling



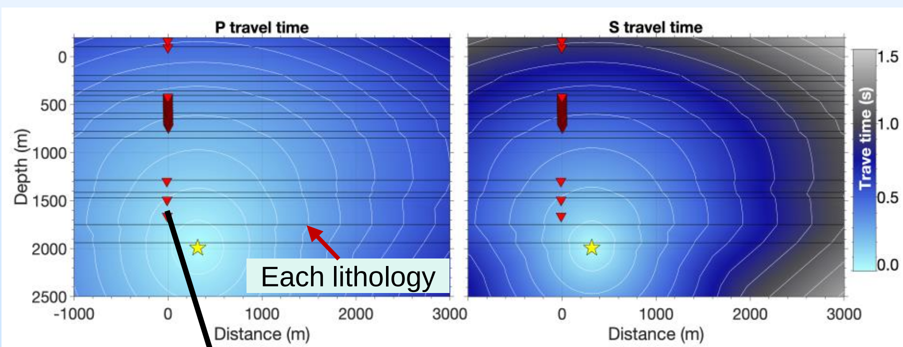
Unsupervised:
Fingerprint-based clustering

- Clustering: acoustic state -> failure mechanisms
- Waveform to spectrogram (short time Fourier transform)
- Non-negative matrix factorization (dimension reduction)
- Hidden Markov model (states)
- State change for clustering using K-means cluster

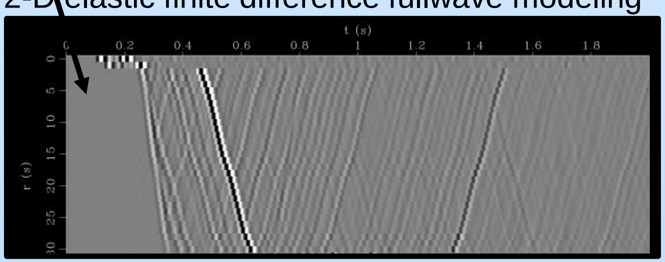
Examples of 3 clusters: June, 2012 identified w/ spectrogram analysis of waveform data. Cluster analyses found correlation between clusters and location (depth, distance, temporal sequence)

Technical Status: Task 3
Inverse Modeling

- Develop and apply Bayesian event location algorithm using wavefield back projection and reliable polarization information.
- Enhanced fault identification and localization by using more events and improved locations.

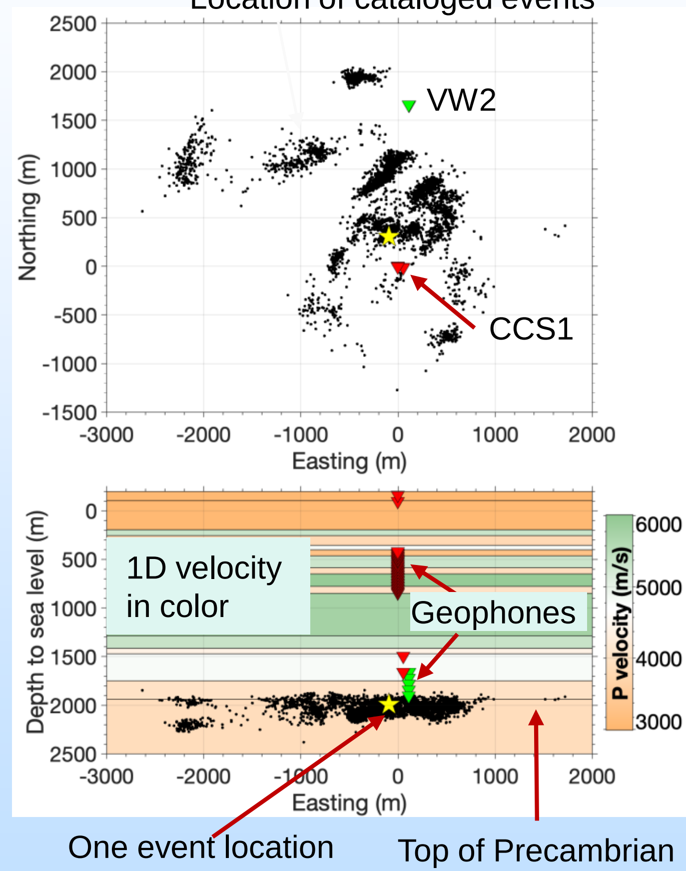


2-D elastic finite difference fullwave modeling



Back projection of P (left) and S (right) wavefields from an event. Most likely location of event is shown in brighter colors. Yellow star indicates best determined location.

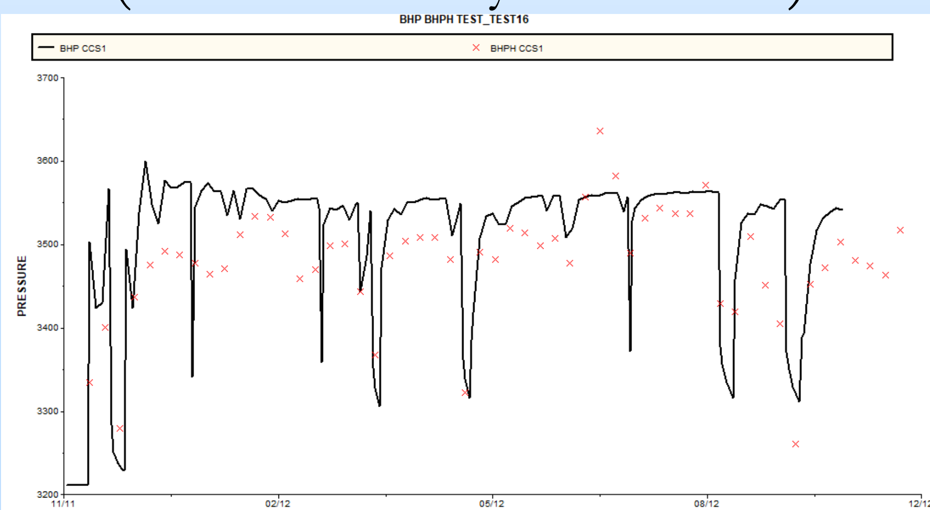
Location of cataloged events

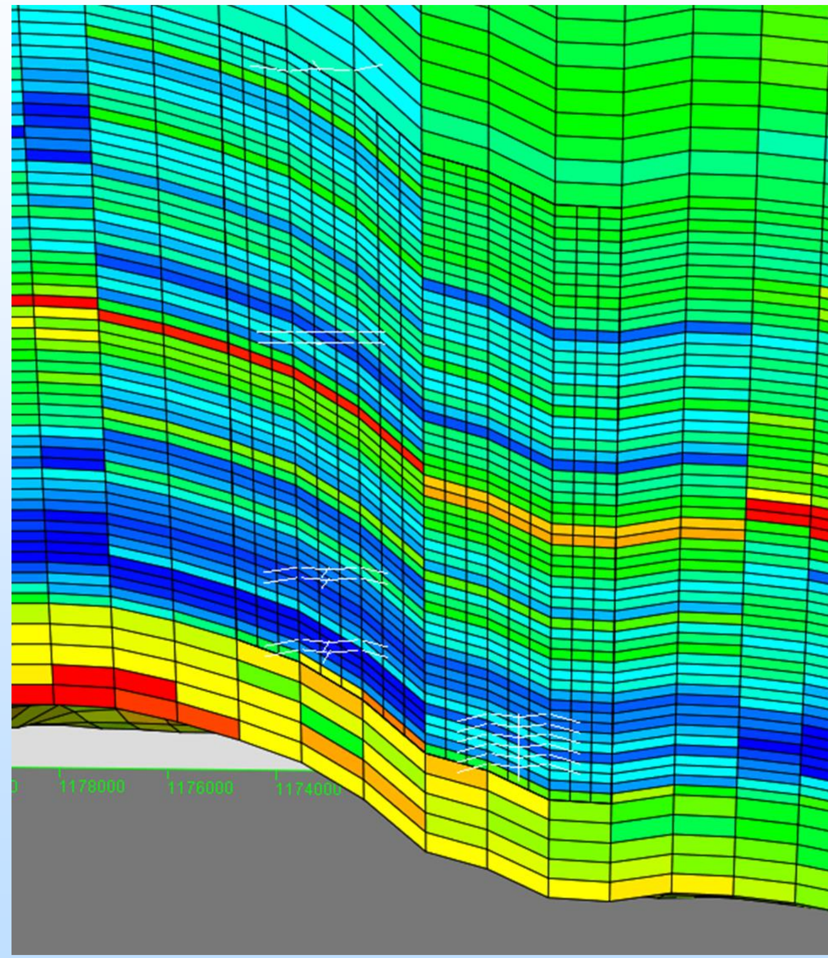


Map view (top) and vertical cross section showing catalog locations. Yellow star shows location of event analyzed on left

Technical Status: Task 4
Large-Scale Pressure Modeling

- Continued calibration process of improving geocellular model to field observation data (pressure, rate, saturation)
- Established process of exporting fluxes to smaller-scale pore-elastic models (outer boundary conditions)

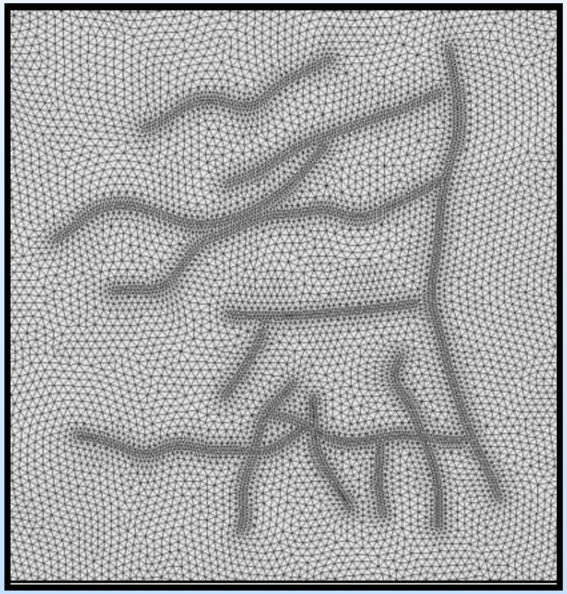




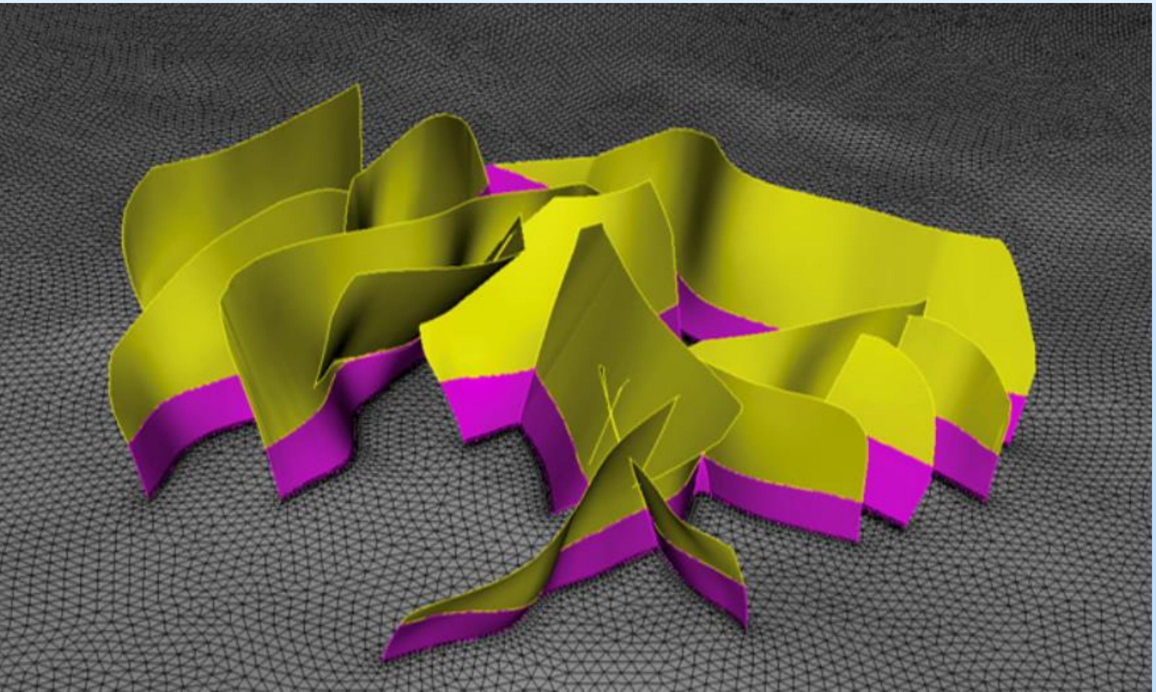
Technical Status: Task 4 Poroelastic Modeling

- Started meshing process for poroelastic modeling of network of faults

2D view: faults and mesh

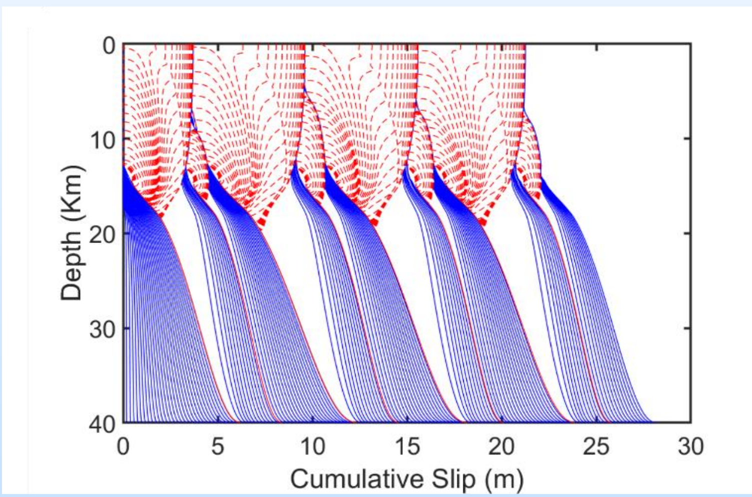


3D view: faults and mesh



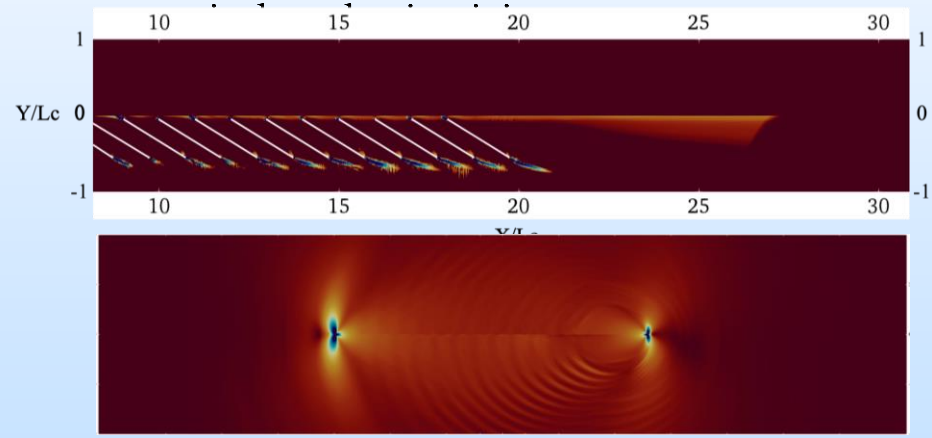
Technical Status – Task 5: Stress Field (Mechanical) Modeling

- Single fault slip (fwd) modeling:
  - Single frictional fault (governed by rate\state friction) embedded in heterogeneous "elastic" rock subjected to stress perturbations
  - Model seismic and aseismic slip.



Slip contour for alternating quasi-dynamic and dynamic approach for the case (c), showing wave reflection. In the slip contours the blue lines are plotted every 5 years during aseismic slip and every 1 second during dynamic rupture.

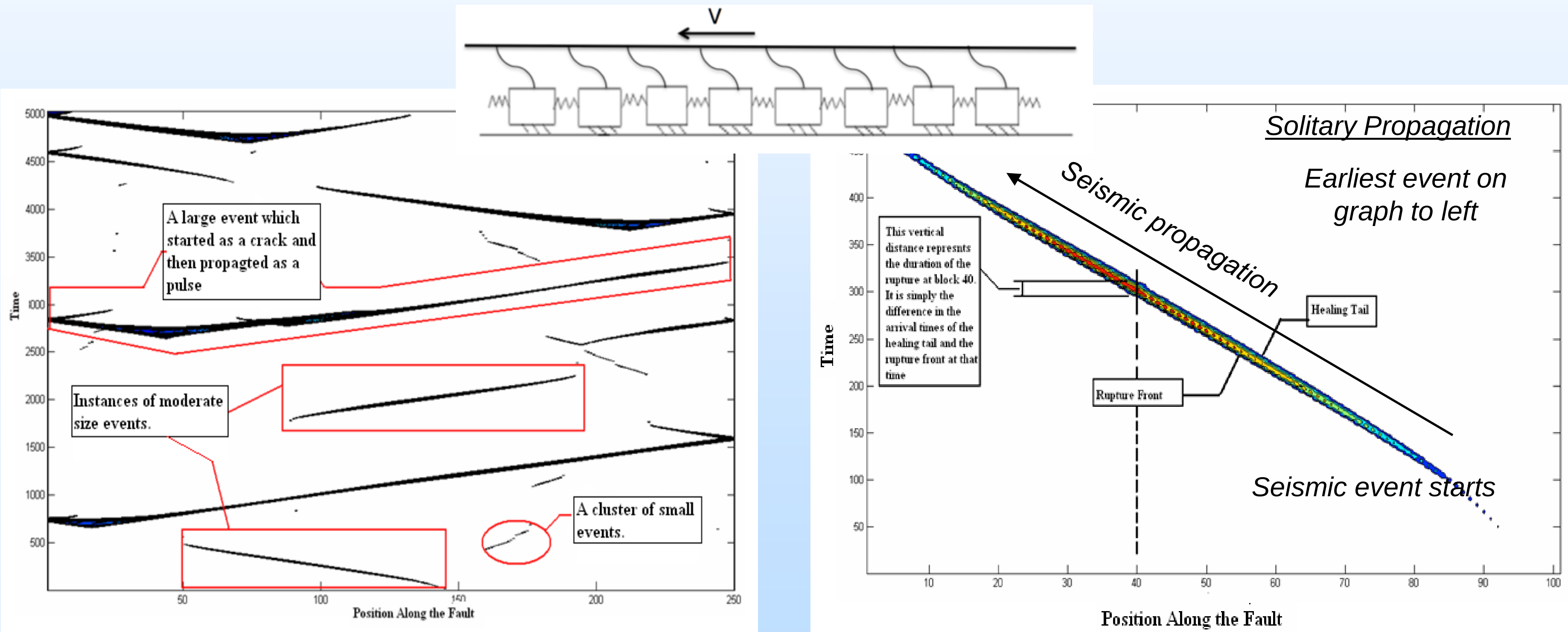
- Fault network (fwd) modeling:
  - Models stress transfer between different faults and spatio-temporal distribution of induced seismicity.
  - Simulates stress state evolution and



Top: Damage distribution and stress concentrations due to slip and activation of multiple faults in a network (Faults are represented by lines and colors represent extent of damage. Bottom: Radiated wave field from the above fault network showing high frequency wave fronts propagating away from the fault.

Technical Status – Task 5: Modeling: Space-time distribution of Seismicity

- <u>Discrete spring-block model:</u> distribution of seismicity including events of different sizes, clustering, and non uniform inter-event times.
- Appropriate for strongly heterogeneous faults but fails to correctly capture long range stress transfer through propagating seismic waves. Thus the results are approximate. Statistically, it generates events of different sizes that propagate is solitary like fashion similar to real earthquakes.



<u>Horizontal line</u>: the distribution of the velocity of fault segments slipping at that time.
<u>Vertical line</u>: velocity at that position on the fault as a function of time
Periods of slip and quiescence (stick slip)

At given time only a narrow part of the fault is slipping simultaneously.
The slope of the line bisecting the contours - avg event rupture speed.
The event generates seismic energy non uniformly: the red contours correspond to the time of more energy generation.

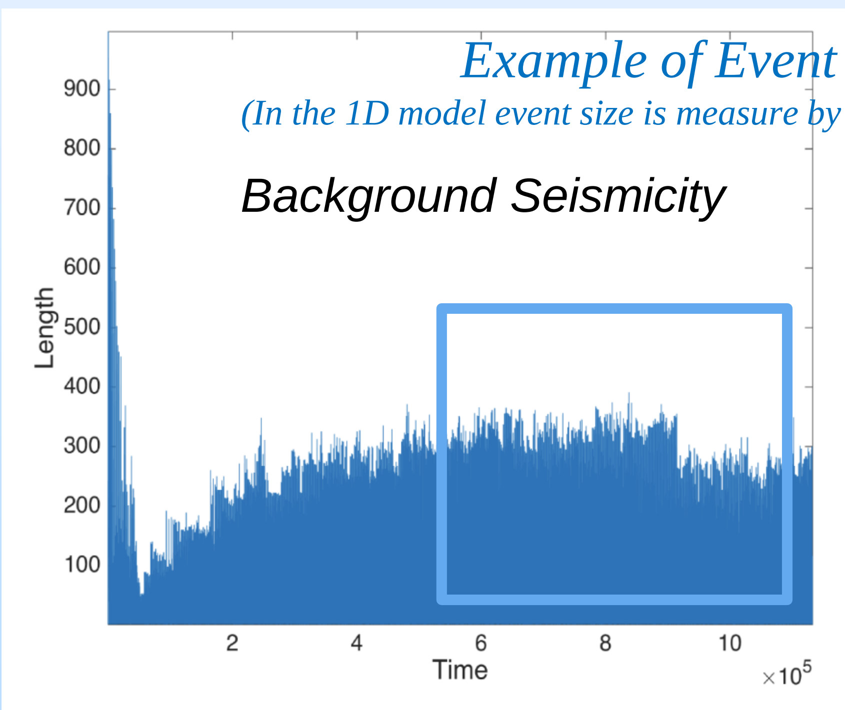
Technical Status: Task 5
Seismic (Waveform) Modeling

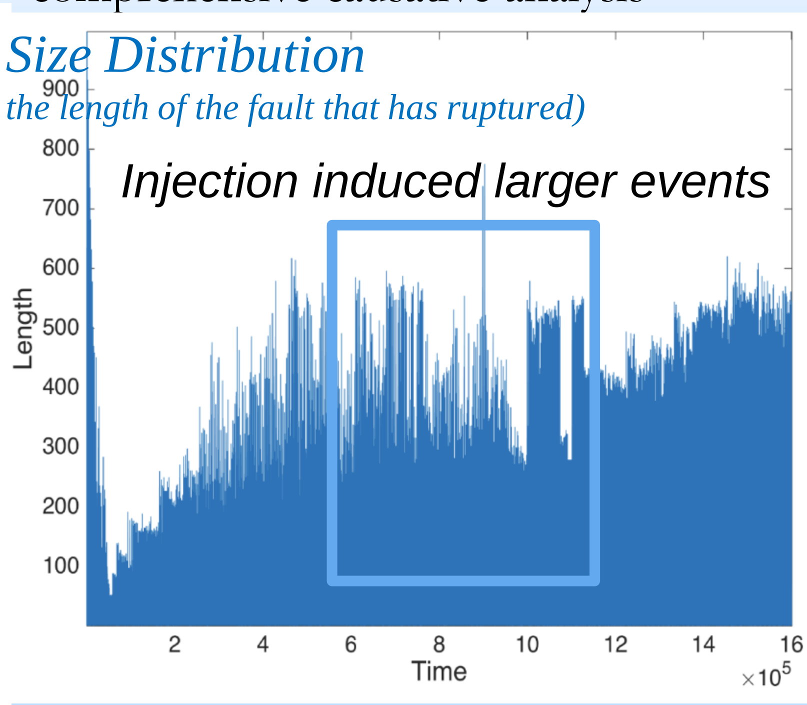
- Continuum models include full physics of fault slip including rate and state friction, inertia effects, inter seismic creep, and bulk heterogeneity.
- Models full sequence of earthquakes and aseismic slip.

- <u>Discrete spring-block model:</u> distribution of seismicity including events of different sizes, clustering, and non uniform inter-event times.
- Effects of injection on seismicity pattern to a zeroth order approximation.
- Continuum models: A more comprehensive causative analysis

Example of Event Size Distribution

(In the 1D model event size is measure by the length of the fault that has ruptured)





Accomplishments to Date

Task 2:

- 3-D stratigraphic framework: ground surface into crystalline basement
- 28 faults added to the geologic model
- High-resolution geocellular model for storage unit and confining zones
- Velocity and geomechanical model: surface to crystallin basement

Task 3:

- Workflow using cont. raw waveform data to detect new events and arrival times using supervised CNN
- Transformed raw four to three orthogonal channel data and estimated source locations using 1D velocity model
- Waveform cluster characterization using unsupervised ML to generate the fingerprints of pattern changes and identify potential fault planes

Task 4:

- Initial representation of faults
- Process of transferring flux data between pressure and poroelastic models
- Preliminary calibration of pressure and saturation with enhanced geocellular model

Task 5:

- Constructed a cellular fault model (aka spring block slider model) to generate realistic seismicity in space and time. Currently using this model to explore the effect of timing, location, and volume of injection on seismicity pattern
- Conducted simulations of earthquake cycles (including seismic events and inter seismic creep) on single faults embedded in heterogeneous media to explore the effect of fault zone compliance on earthquake sequence.

Lessons Learned

-Pressure Modeling: small scale geologic features (e.g. thin baffle and barriers) must be included and not “invisible” due to upscaling or grid selection.

- Supervised and unsupervised ML improve detection of events and potentially identify the waveform characteristics associated with induced seismic mechanisms
- Data analytics can be achieved using open-source framework to handle big cont. waveform data analysis

- Essential to consider in-situ stress heterogeneities as well as small scale heterogeneities in material and frictional properties
  - dominant roles in controlling microseismicity
  - challenge is that these heterogeneities are difficult to measure directly and include in geocellular models and effected by upscaling

Project Summary

Key Findings

– Calibrating model to wells in close proximity requires precise, small-scale features present in the geocellular model, even in the presence of relatively coarse grid cells.

– Unsupervised ML clustering may be applicable to identifying microseismic characteristics associated with the fault/fracture instability mechanisms

– Dynamic feedback exists between fault stress heterogeneity and seismicity pattern.

  - heterogeneous stress may lead to arrest of seismic events before becoming fault-spanning event (i.e. make them localized).
  - leads to stress concentration at the fault tips which may promote nucleation of future events.

– Traditionally located fault (i.e. surface seismic) and those located via microseismicity are not consistent.

Next Steps

- Incorporate faults identified from ML into the geocellular model and validate in conceptual geologic model.
- Automate cont. raw waveform data processing for new event detection and arrival time estimation
- Improve the accuracy of source location estimation using updated velocity model(s) and ML analytics w/ pressure and stress fields
- Perform coupled flow geomechanics simulations to assess the impact of fault property variation (e.g. fault perm) on pressure and stress field near faults
- Extend the simulation of earthquake cycles to geometrically complex fault networks while accounting for effect of permeability anisotropy and heterogeneity in damaged fault zones. The latter will use simulation outputs for pore pressure distribution from MIT and ISGS.
- Identify characteristics of faults that are more likely to release seismic energy

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Appendix:
Project Benefits Statement

- This project is supportive of AoI 2- Methods for Understanding Impact of Vertical Pressure Migration due to Injection on State of Subsurface Stress.
- Mechanisms of transmitting pressure and stress vertically from a storage unit to a fractured and faulted crystalline rock will be identified via a series of unique modeling efforts that are calibrated to injection results at a DOE sponsored demonstration project.
- Identification of characteristics of faults that are more likely to release seismic energy upon injection will lead to technology development that can identify these characteristics a priori to injection at specific sites.

Appendix: Project Overview

Goals and Objectives

- To predict the presence of faults that will be susceptible to movement in the presence of fluid injection as a consequence of vertical pressure migration from the storage unit to the crystalline basement (underburden).
  - *BP1 (Year 1):* Complete at least one initial geocellular model for each of the three forward modeling efforts and complete initial assessment of fault locations using machine learning and based on joint inversion modeling using Illinois Basin Decatur Project (IBDP) microseismic data.
  - *BP2 (Year 2):* Complete at least one static model (predicted) of pressure and stress in the storage unit, across the geologic interface between the storage unit and the faulted crystalline basement, and the faulted crystalline basement, and identify effective techniques to represent faults and fault zones in geocellular models based on conceptual geologic models.

Appendix: Project Overview

Success Criteria

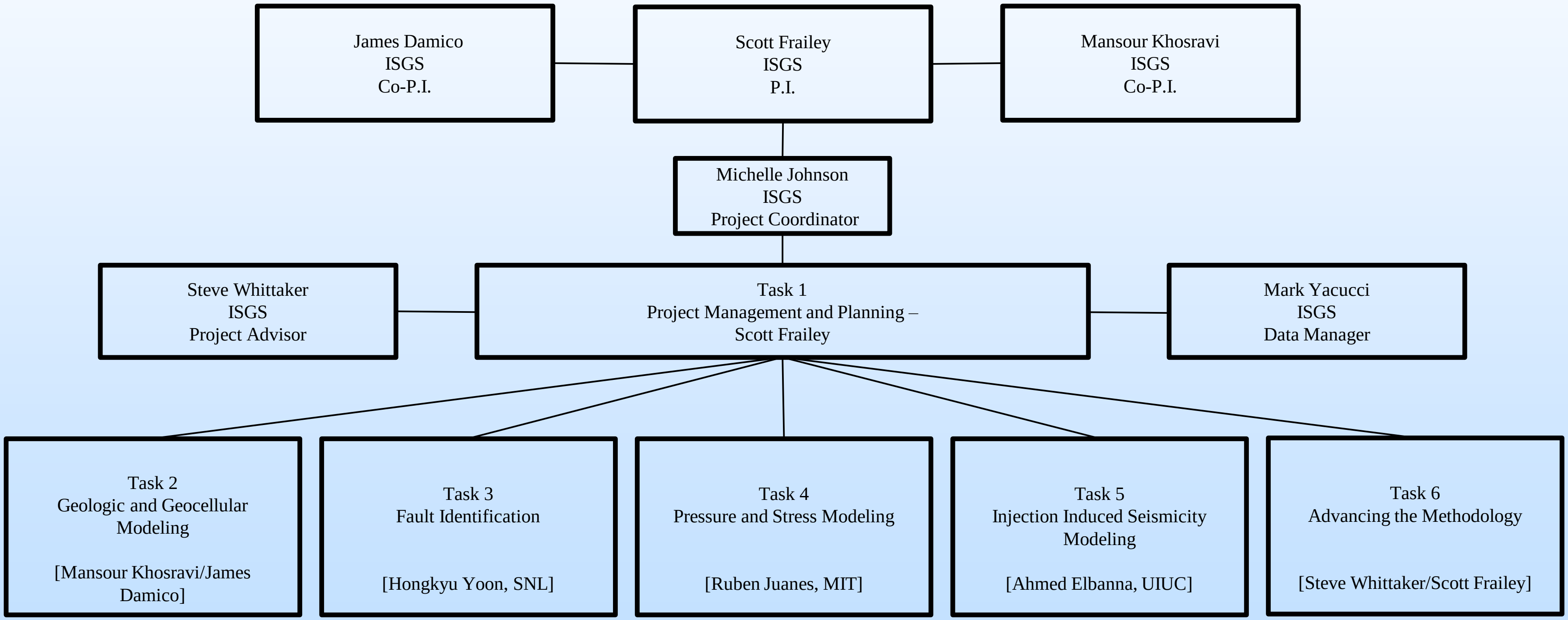
- *BP 1*: The initial geocellular models will be assessed as being successful upon completion and review by the project team. The initial fault model produced via inverse methods will be judged successful by the identification of any faults through inversion methods.
- *BP 2:* The initial model of pressure and stress will be assessed as being successful by completion and convergence with microseismic data. The updated geocellular model with faults will be assessed as being successful by completion of a new model that incorporates faults identified in the conceptual model and review by the project team.

Appendix: Project Overview, contd.

Success Criteria

- *BP 3:* Data-driven fault models produced by the machine learning process will be assessed as being successful by the presence of newly identified faults that agree with the seismic data characteristics and the forward and inverse modeling results. The summary of findings will be assessed as being successful by completion and acceptance by the funding administration of the final report and the submission of one paper on the major findings of the project to a peer-reviewed scientific journal.

Appendix: Organization Chart



Appendix: Gantt Chart

		2018	2019				2020				2021		
Task	Responsible Party	4	1	2	3	4	1	2	3	4	1	2	3
Task 1.0 – Project Management and Planning													
1.1 Kickoff, monthly task leader, and monthly task meetings	Task Leaders, Johnson												
1.2 - Quarterly reports and project meetings	Task Leaders, Johnson, Prete												
1.3 – Annual DOE reports and meetings	Task Leaders, Johnson, Prete												
Milestone: Project Management Plan	Frailey & Johnson	100%											
Task 2.0 – Geologic and Geocellular Modeling													
2.1 – Comprehensive review of existing models	Kosravi, Damico	100%											
2.2 – Conceptual geologic models of storage unit and crystalline basement	Kosravi, Damico	100%											
2.3 –Geocellular modeling techniques for creating 3D models of hydraulic, mechanical, and seismic rock properties within the framework of the architecture of the geologic conceptual model	Kosravi, Damico	75%											
2.4 –Geocellular representation of the conceptual geologic model based on characterization data	Kosravi, Damico	15%											
Subtask 2.5 – Geologic and geocellular model realizations based on forward and inverse stress and pressure modeling	Kosravi, Damico	25%											
Milestone: Initial geocellular models	Kosravi, Damico	100%											
Milestone: Update of geocellular models with faults	Kosravi, Damico	0%											
Task 3.0 – Fault Identification	Yoon & MIT												
3.1 – Detection of microseismic events	Yoon & MIT	50%											
3.2 – Characteristics of microseismic events	Yoon & MIT	40%											
3.3–Bayesian inversion of time-lapse microseismicity data into coupled flow-geomechanics models	Yoon & MIT	10%											
3.4 - Rapid recognition of the presence of (undetected) faults and fault interactions using deep learning approach	Yoon & MIT	0%											
Milestone: Initial assessment of fault locations	Yoon & MIT	35%											
Go/No-Go Point 1 - Identification of Faults via multivariate inverse modeling	Yoon & MIT												
Milestone: Validate fault model with seismic data/conceptual model	Yoon & MIT	0%											
Go/No-Go Point 2 - Identification of Faults via machine learning	Yoon & MIT												
Task 4.0 – Pressure and Stress Modeling													
4.1 – Pressure perturbation	Juanes	40%											
4.2 – Fracture flow	Juanes	0%											
4.3 – Stress perturbation	Juanes & Frailey	0%											
Milestone: Initial model of pressure and stress	Juanes	10%											
Task 5.0 – Injection Induced Seismicity Modeling													
5.1 – Curation of input data and model output	Elbana & Juanes	15%											
5.2 – Fault slip modeling	Elbana & Juanes	45%											
Go/No-Go Point 3 - Fault slippage via seismicity modeling	Elbana & Juanes												
5.3 – System level seismicity modeling	Elbana & Juanes	50%											
5.4 – Development of conceptual model for induced seismicity	Elbana & Juanes	0%											
5.5 – Model Validation and updating	Elbana & Juanes	0%											
Task 6.0 – Advancing the Methodology													
6.1 – Field site calibration	Task Leaders	20%											
6.2 – Improvement over current state-of-the-art to identify	Task Leaders	0%											
Milestone: Summary of findings	Task Leaders, Johnson, Prete	0%											