Identification of Faults Susceptible to Induced Seismicity

Project Number DE-FE0031685

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U.S. Department of Energy

National Energy Technology Laboratory

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Project Team

- 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)

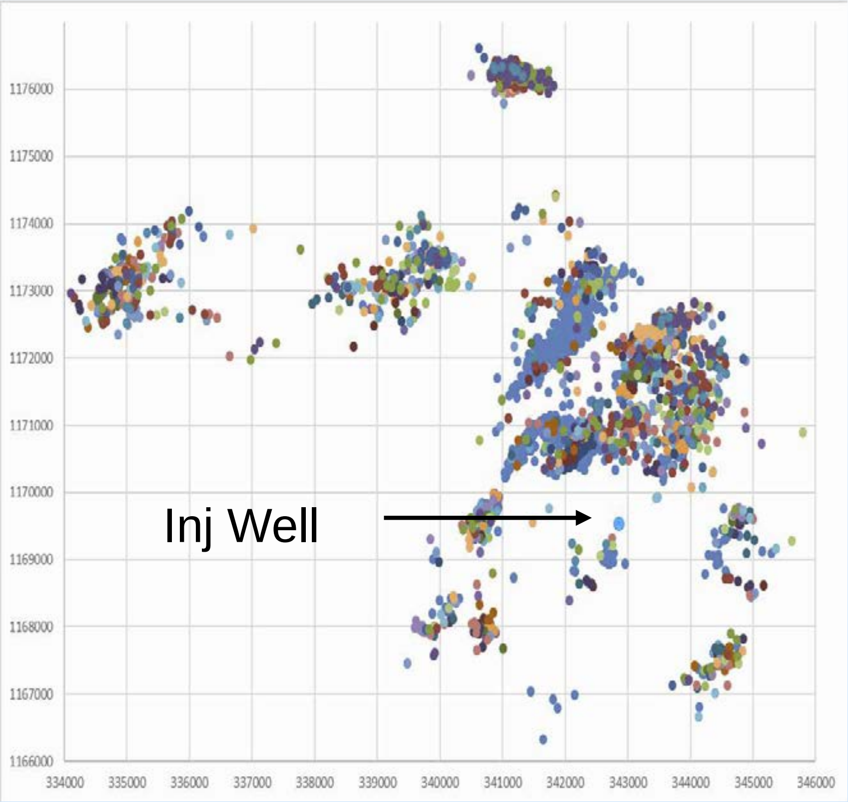
Presentation Outline

- Motivation, Objective, and Approach
- Technical Status 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

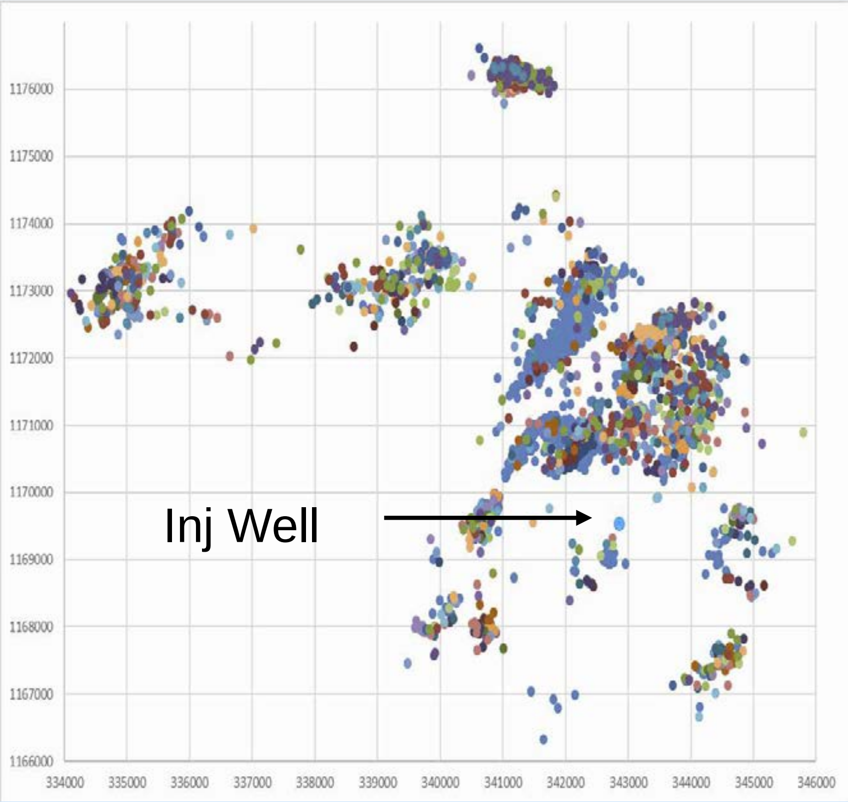


1000 x 1000 ft squares

Objective

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

IBDP Site after 3 yrs injection



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Approach

- Test a series of, **geologically based**, integrated forward and physics-constrained, data-driven (inverse) models that includes the following:
  - a geologically well-characterized field site with microseismicity located within the basement rock,
  - predictions of temporal and spatial stress changes induced by injection,
  - methodology to better resolve basement faults including undetected faults, and
  - identification of mechanisms, which control and transmit pressure from the storage unit to the basement

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

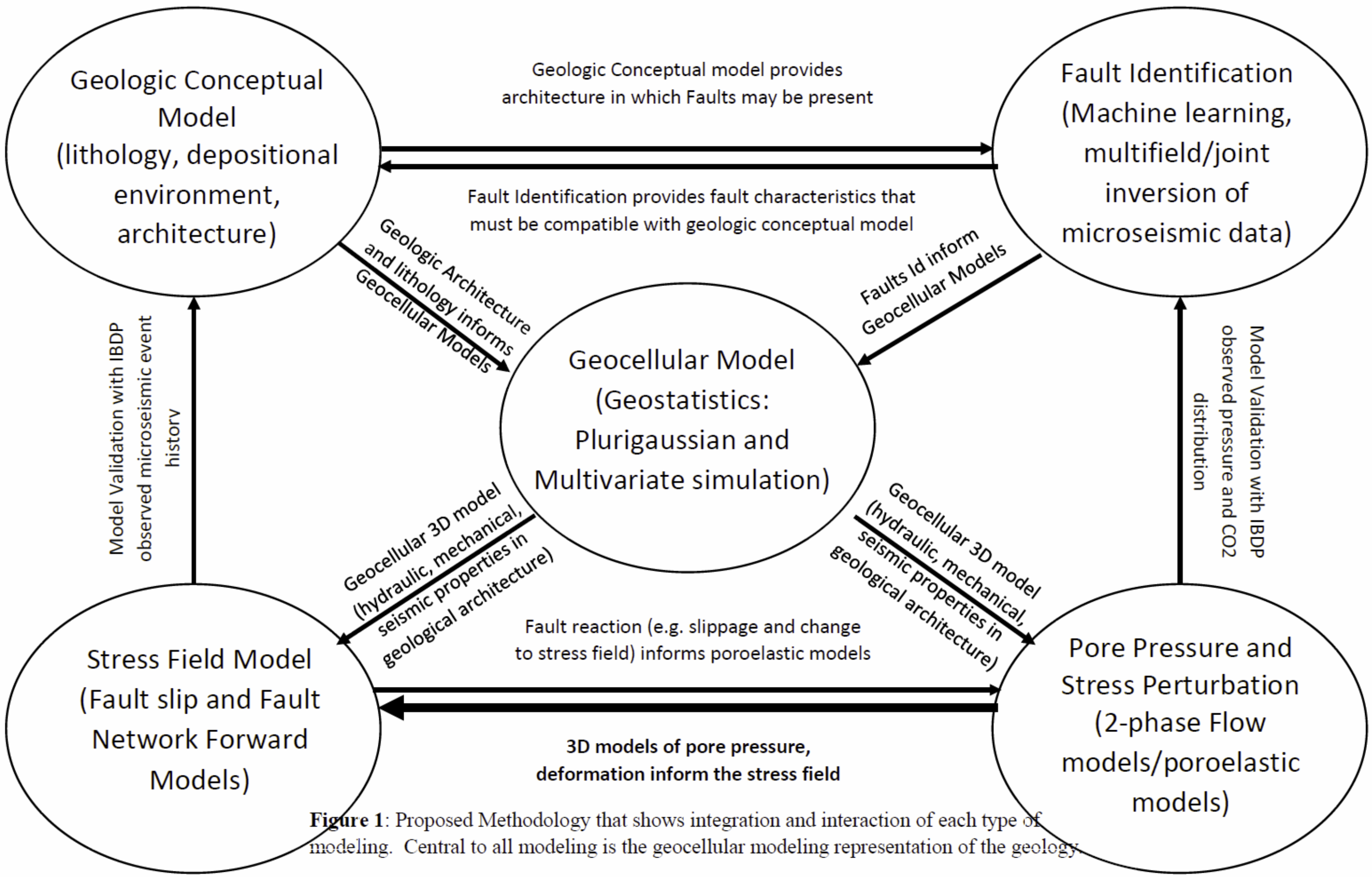


Figure 1: Proposed Methodology that shows integration and interaction of each type of modeling. Central to all modeling is the geocellular modeling representation of the geology.

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

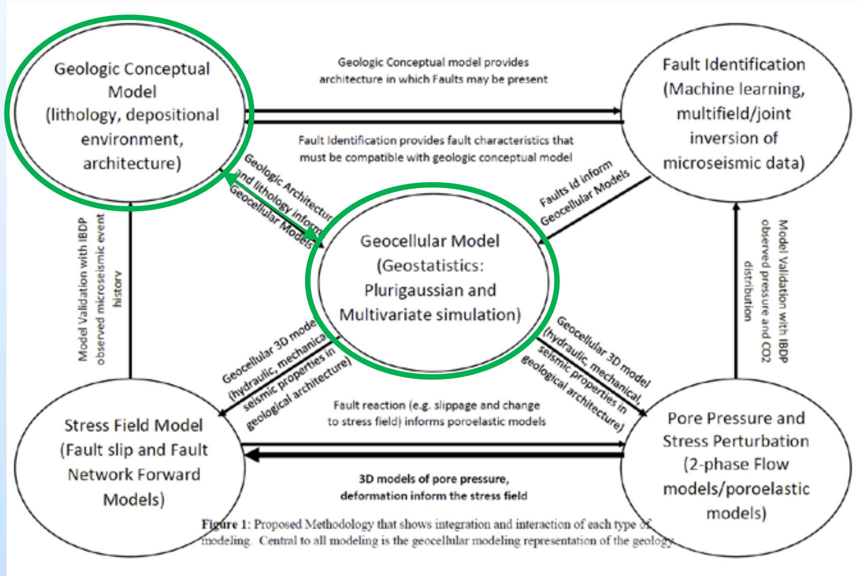
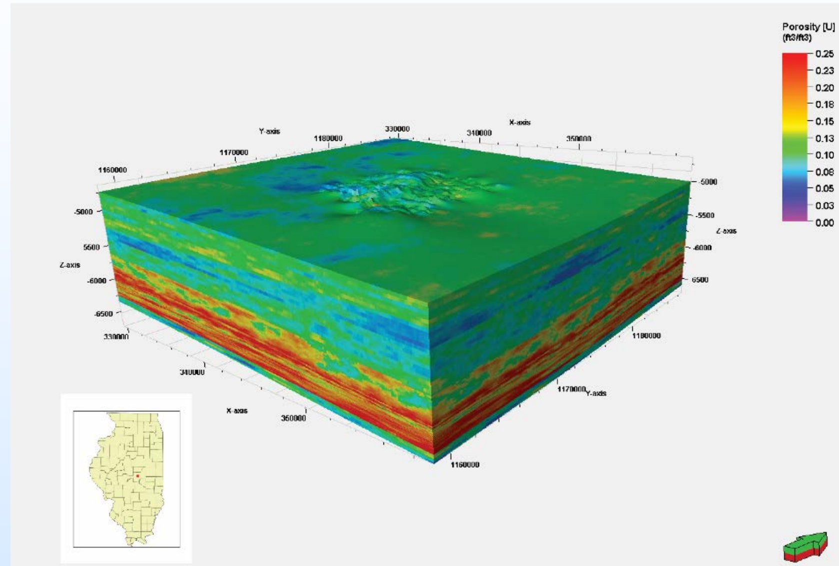
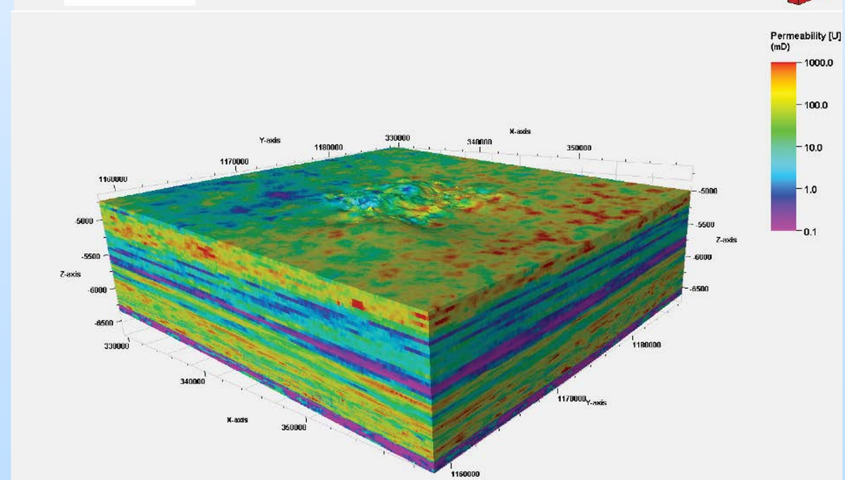


Figure 1: Proposed Methodology that shows integration and interaction of each type of modeling. Central to all modeling is the geocellular modeling representation of the geology.

Technical Status: Task 2 Key Points

- Defined geocellular model parameters across all tasks
- Characterized geology of formations overlying and underlying injection reservoir
- Finalized initial fault model based on traditional geophysical approaches
- Built geocellular model using geostatistics, conceptual geologic model





Technical Status: Task 3
Fault Identification Modeling

- Improve detection of low-magnitude events to discover undetected fault/fracture
- Characterize waveforms' relations among events, identify event locations with forward/inverse modeling
- Apply Bayesian inversion algorithms on coupled flow-geomechanics models
- Identify range of parameters that yield flow model results consistent with geocellular model

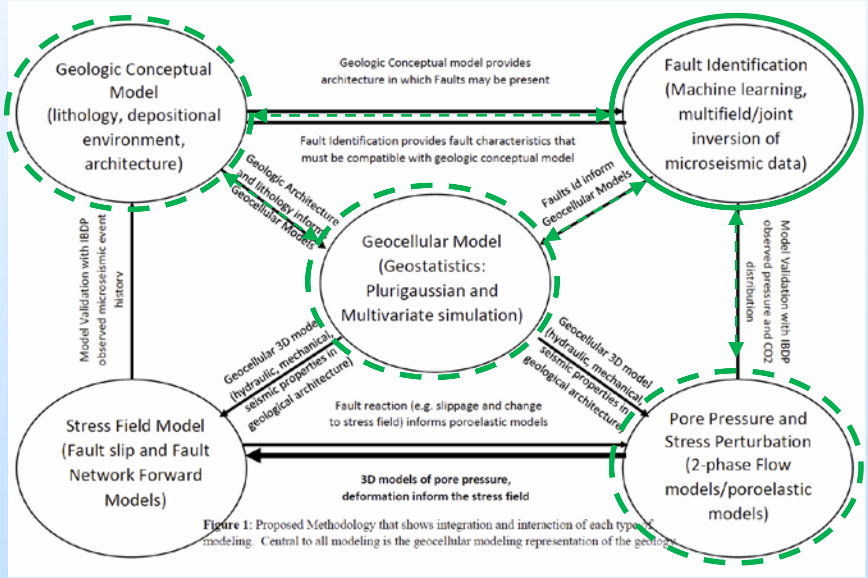
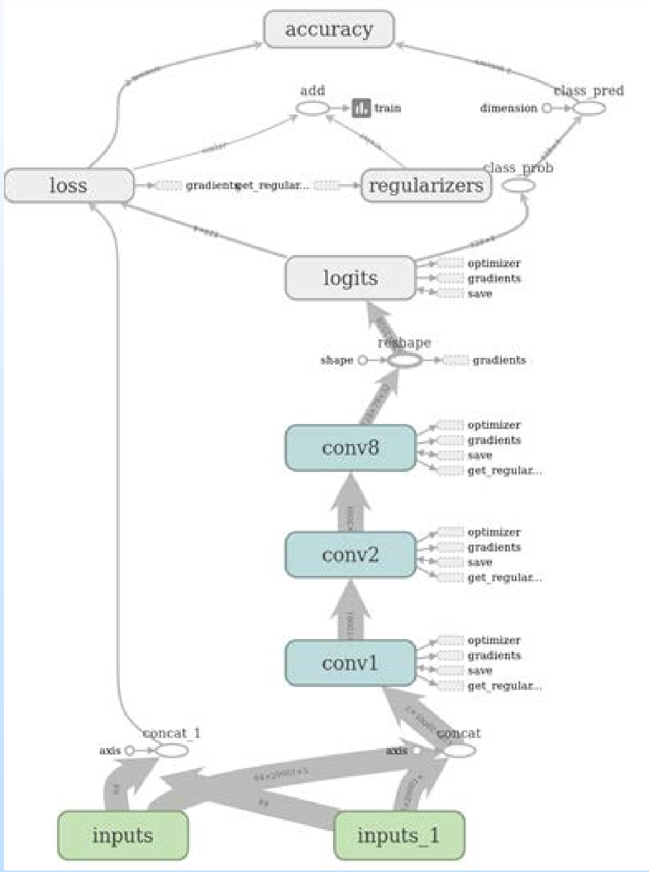


Figure 1: Proposed Methodology that shows integration and interaction of each type of modeling. Central to all modeling is the geocellular modeling representation of the geology.

Technical Status: Task 3 Key Points

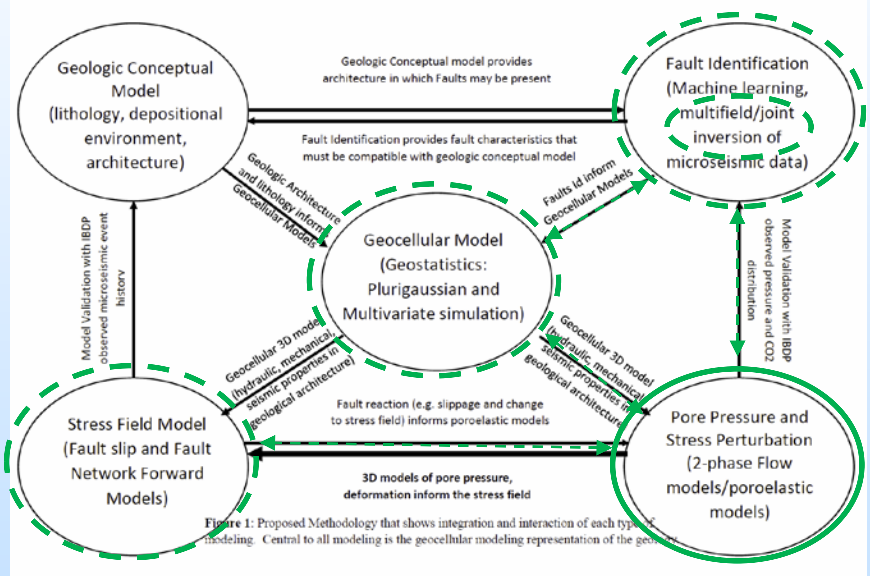
- Established workflow to convert waveform data to format appropriate for each machine learning model (each algorithm requires a different format)
- Started using a template-matching waveform analysis model (EQcorrscan) to characterize the waveforms of events detected



CNN structure

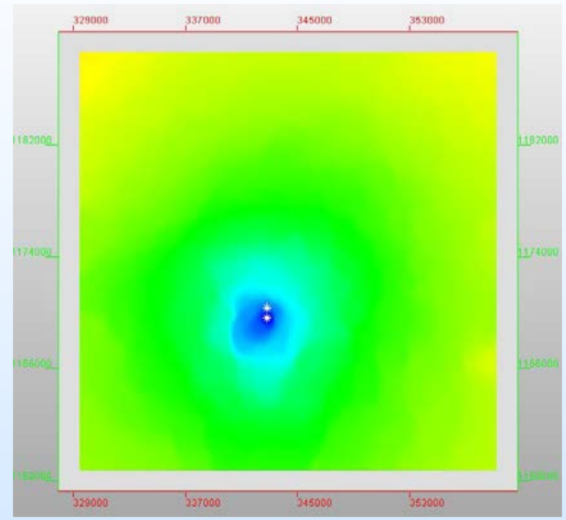
Technical Status: Task 4
Pore Pressure Modeling

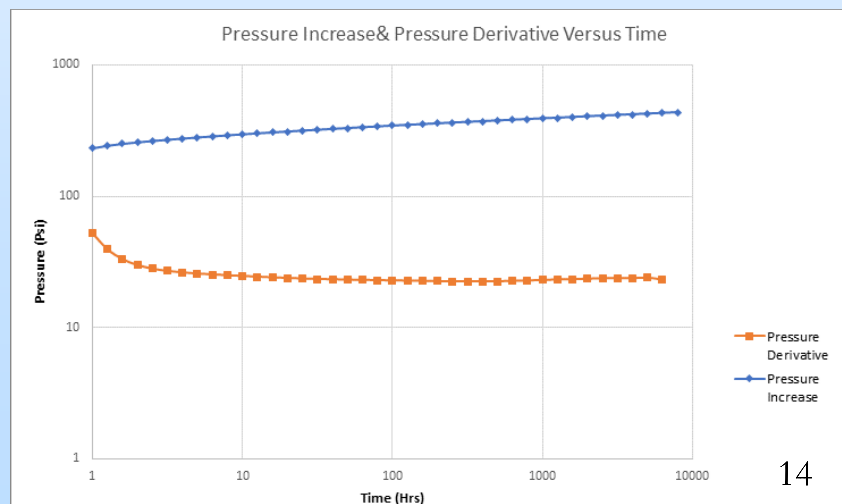
- Pressure modeling (large models):
  - Boundary conditions for geomechanically coupled, stress, and fault models
- Poroelastic (forward) modeling:
  - coupled flow-geomechanics
  - simulate static and dynamic stress evolution
- Calibrate to IBDP observations



Technical Status: Task 4
Key Points

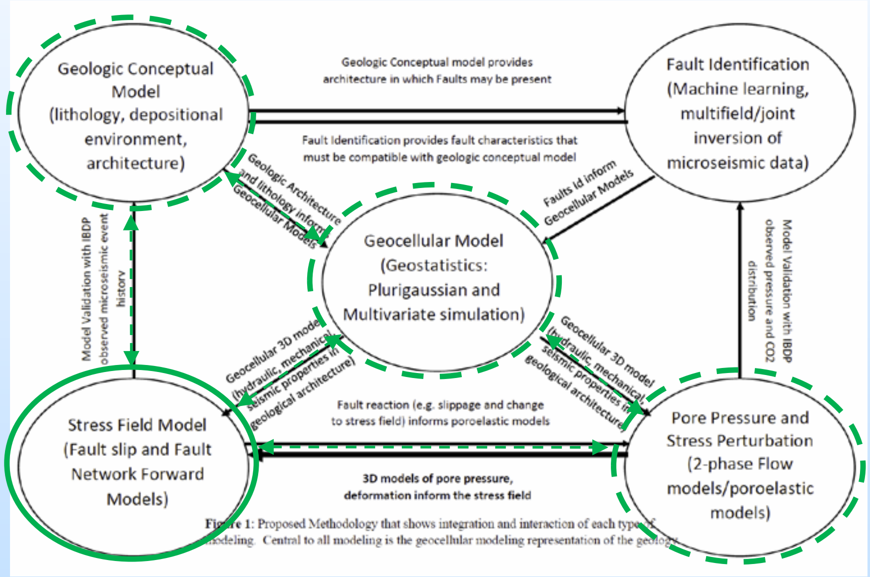
- Defined fluid and rock properties
- Calibrated aquifer function at model boundary
  - Infinite-acting model
- Conducting history matching of injection and monitoring wells: pressure, injection rate, and saturation profiles





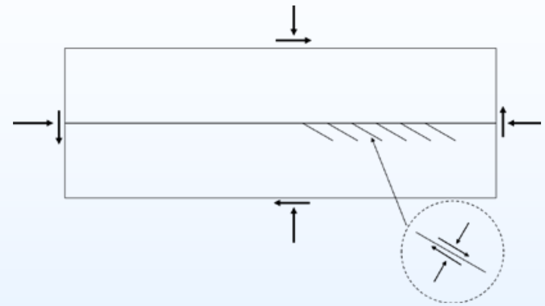
Technical Status – Task 5: Stress Field (Mechanical) Modeling

- Model single fault slip (fwd:
  - Single frictional fault (governed by rate\state friction) embedded in heterogeneous "elastic" rock subjected to stress perturbations (i.e., injection)
  - Model seismic and aseismic slip.
- Model fault network (fwd):
  - Models stress transfer between different faults and understand spatio-temporal distribution of induced seismicity.
  - Simulates stress state evolution and induced seismicity

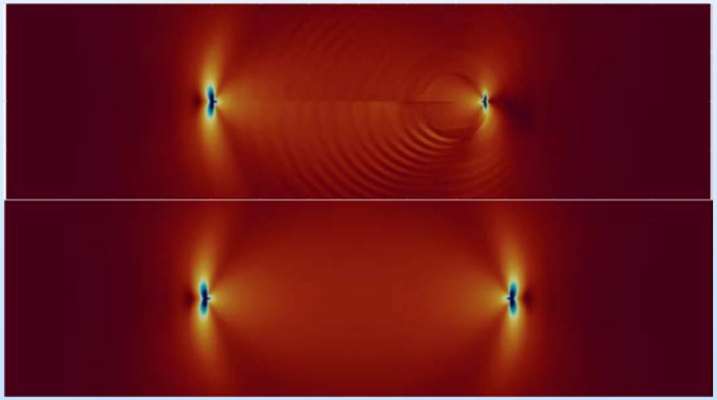


Technical Status: Task 5 Key Points

- Developed numerical scheme (Finite Element and Spectral Boundary Integral eqs)
  - Enables high resolution modeling of earthquakes in complex fault zones
  - Models interaction of multiple fractures
- Extended scheme to model pre-seismic creep, rapid seismic slip, and post-seismic relaxation
  - Enables modeling fault interaction and state of stress evolution w/ time
  - Essential for characterizing seismic hazard due to injection



Example of a fault zone with a main fault and small branches (fish bone structure).



Bulk Particle velocity from a complex fault (top) and planar fault (bottom). Note the high frequency fringes propagating further in the top plot.

Accomplishments to Date

Task 2:

- Completed detailed geologic characterization of the Precambrian crystalline basement (PCB)
- Established grid type and dimensions for use across tasks
- Initial geocellular model of petrophysical properties made to represent the geologic conceptual model

Task 3:

- Established data formats for machine learning applications of preprocessed waveform data
- Tested key machine learning (deep learning) algorithms; validated on various computing systems with updated functions

Task 4:

- Identified model grid and cell dimensions
- Completed sensitivity analysis on dimensions and characteristics of geologic features
- Developed spreadsheet tools to simplify calibration tests
- Continued calibration process to enhance geologic/geocellular model

Task 5:

- Tested single fault model to observe the interaction between seismic event propagation, fault creep, and seismicity patterns on a single fault.
- Tested multi-fault model for occurrence and presence of supershear

Lessons Learned

- Small geologic features (< grid cell size) that influence historical observations, may be “averaged” out of the geocellular model, difficult to know, pre-calibration which may be most influential
- The precise waveform dataset required for machine-learning processes was not immediately identified and presented several logistical challenges in transferring data between institutions

Synergy Opportunities

- Comparison of workflow and algorithms with those using machine learning.
- Comparison of geologic representation of faults and near-fault regions in geocellular models

Project Summary

Key Findings

– Use of the geologic and geocellular model constrained to the data and generalizations of depositional environment, as a “variable” to match observations works well

– Subtle changes in fault structure (e.g., existence of short branches) may lead to enhancement of high frequency generation (1-20 Hz).

Next Steps

- Finalize “initial” geologic / geocellular model that matches historical data
- Distribute geomechanical and acoustic properties in the geocellular model
- Start poroelastic flow model using geocellular model and pressure modeling boundary conditions
- Apply machine learning algorithms to find pre-event waveform characteristic patterns to periods of time with known and no events

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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

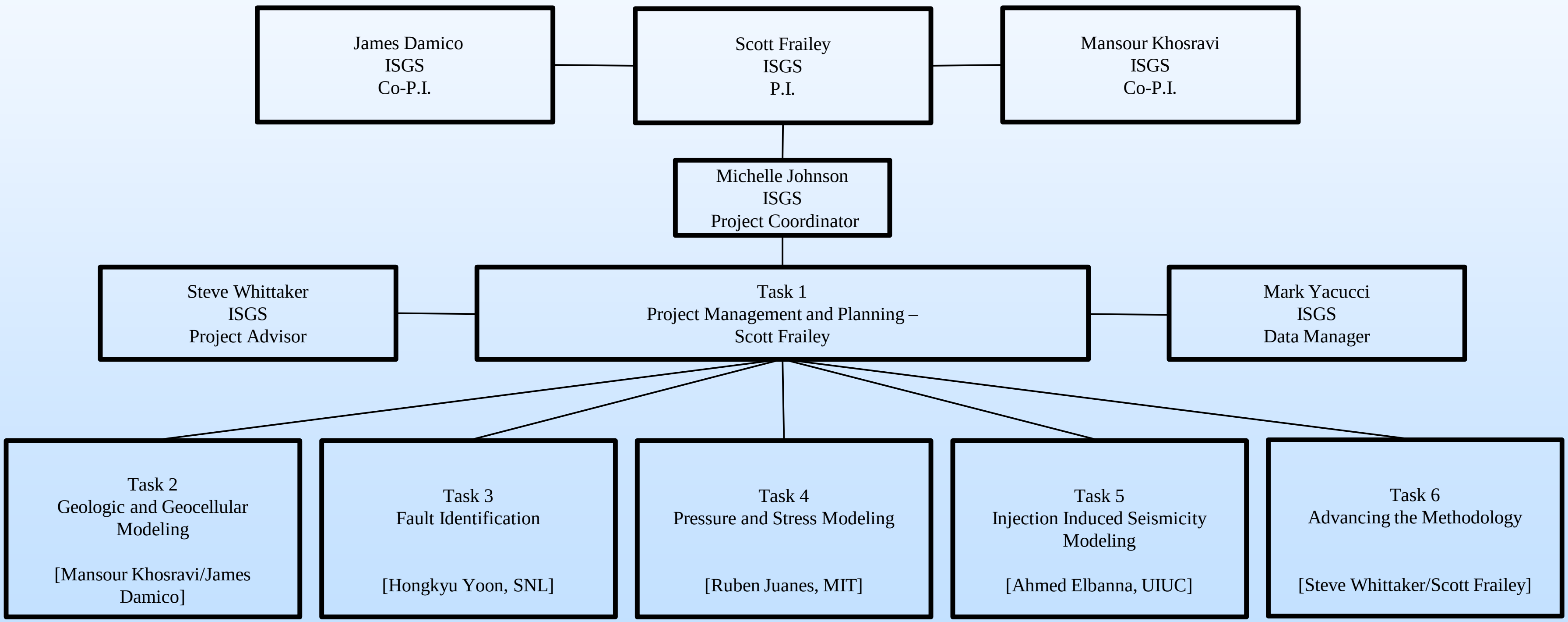
- *BP 1*: The initial geocellular models will be assessed as being successful upon completion and review by the project team. The initial fault model produced via inverse methods will be judged successful by the identification of any faults through inversion methods.
- *BP 2:* The initial model of pressure 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%											

Appendix: Bibliography

- Ma, X., and Elbanna, A. E., 2019, Dynamic Rupture Propagation on Fault Planes with Explicit Representation of Short Branches. Earth and Planetary Science Letters, available at: https://eartharxiv.org/xesnz

- Abdelmeguid, M., Ma, X., and Elbanna, A. E., 2019, A Novel Hybrid Finite Element-Spectral Boundary Integral Scheme for Modeling Earthquake Cycles: Application to Rate and State Faults with Low-Velocity Zones. Journal of Geophysics Research, available at: https://eartharxiv.org/xwhbs