Identification of Faults Susceptible to Induced Seismicity

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Project Participants

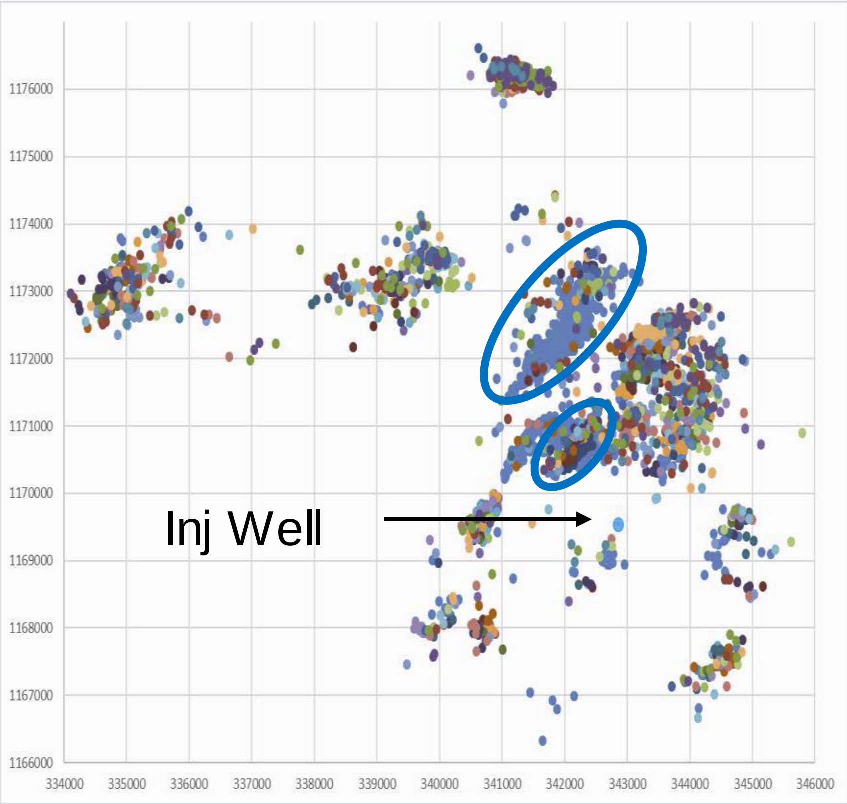
- Geologic and geocellular modeling (Task-2)
  - Mansour Khosravi, James Damico (ISGS)
- Fault identification (Task-3)
  - Hongkyu Yoon (Sandia) machine learning
  - Michael Fehler (MIT) inversion modeling
- Pressure and stress perturbation modeling(Task-4)
  - Ruben Juanes (MIT)
  - Ola Babarinde, Scott Frailey (ISGS)
- Stress field modeling (Task-5)
  - Ahmed Elbanna (UIUC)

Task leaders, underlined

Motivation

- IBDP: 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



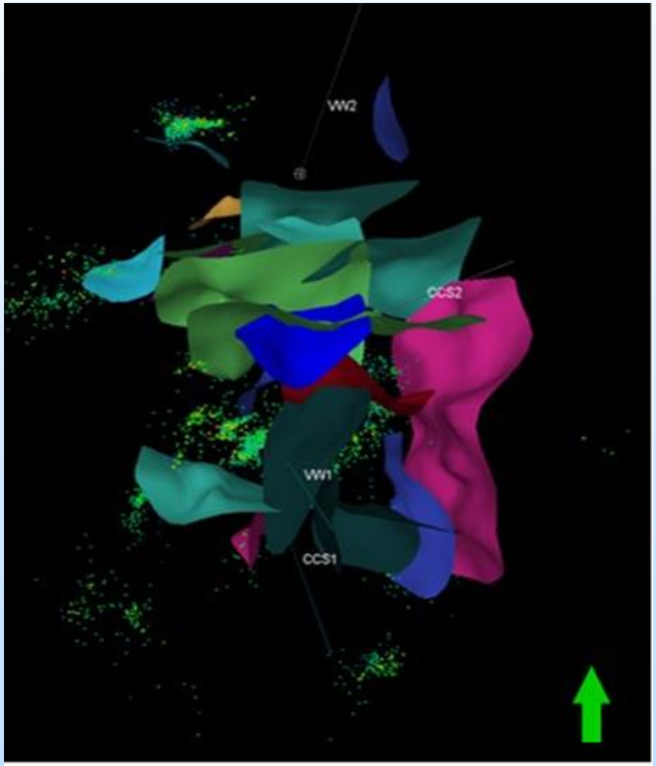
After R. Bauer, ISGS

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 Located using 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 injection intervals 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

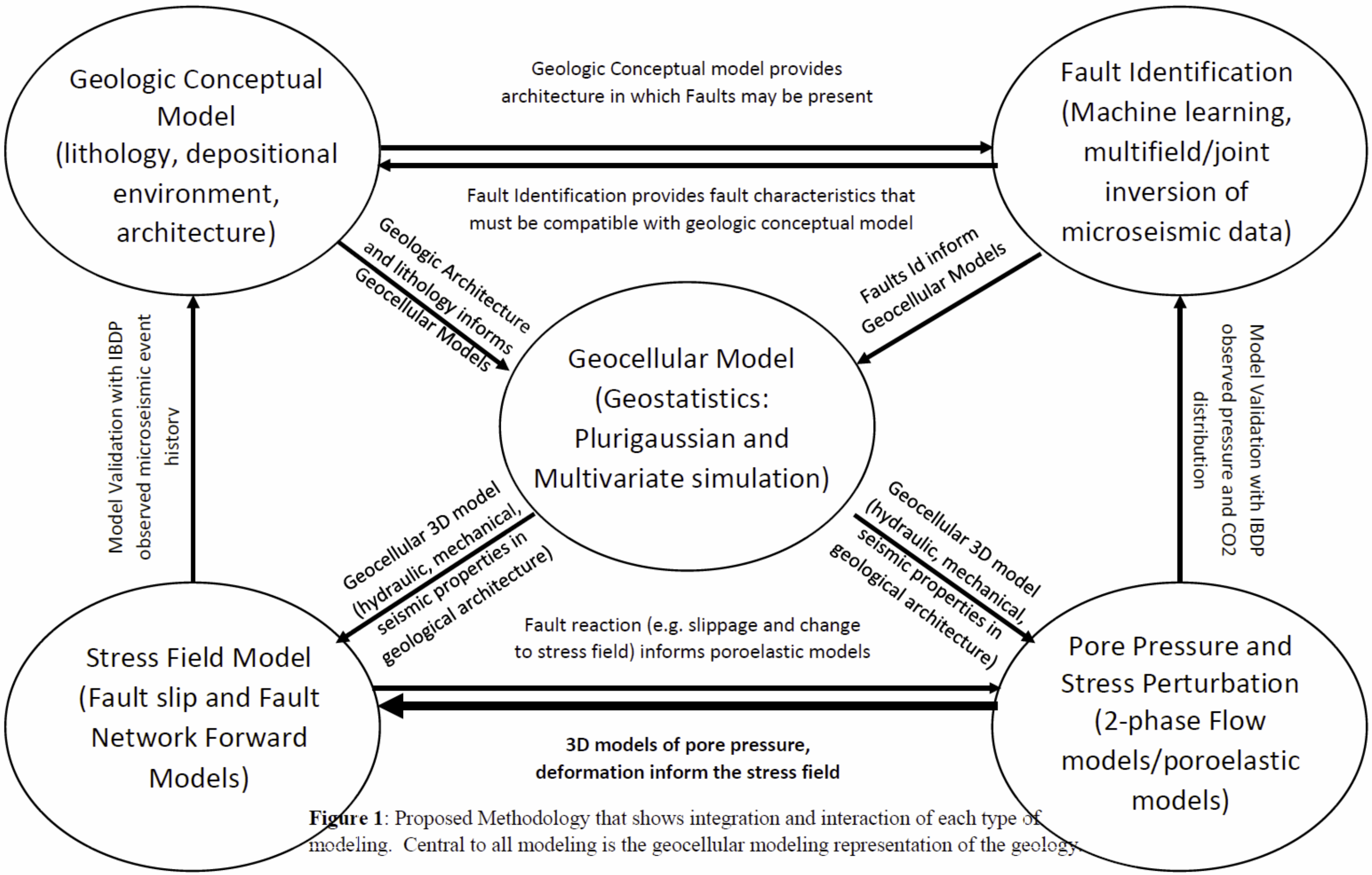
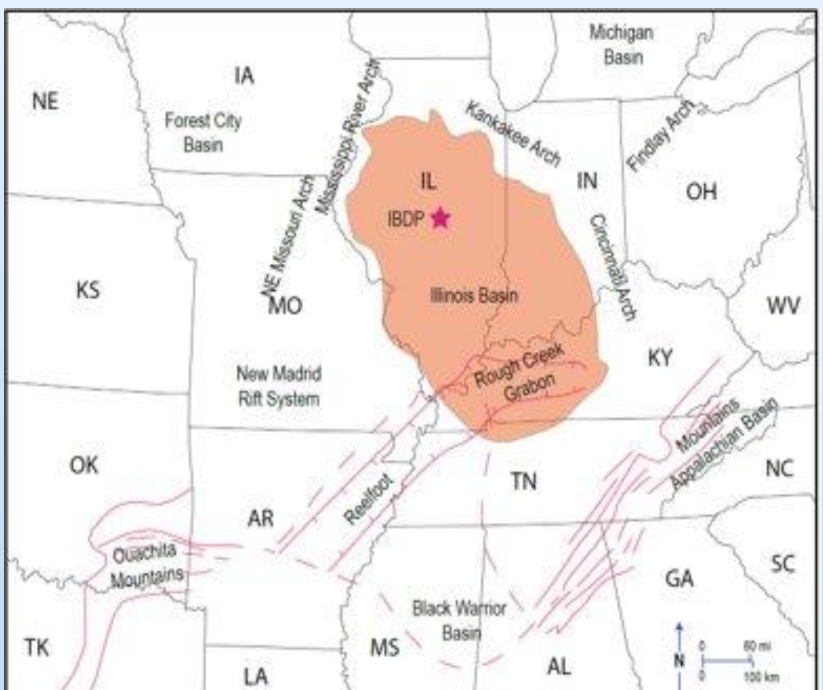


Figure 1: Proposed Methodology that shows integration and interaction of each type of modeling. Central to all modeling is the geocellular modeling representation of the geology.

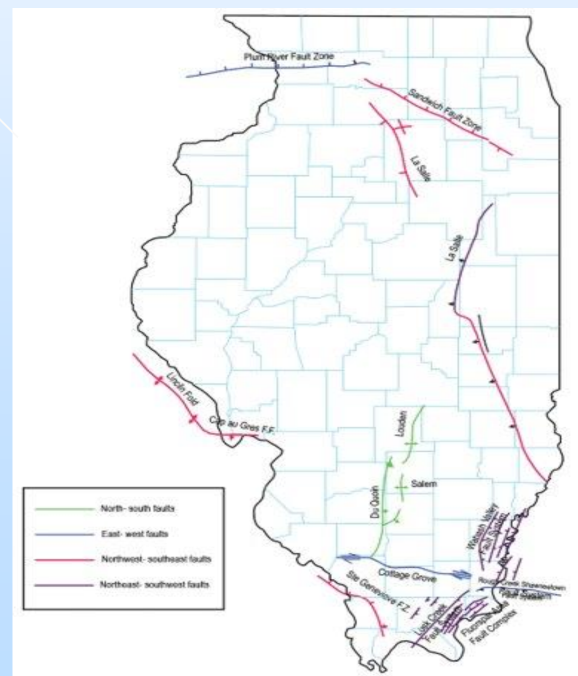
Technical Status: Task 2
Geologic Conceptual Modeling

- Faults detected w/ traditional methods (surface seismic) had **no** recorded induced seismicity
- Faults inferred from induced seismicity, **not** detected by traditional methods
- Workflow iteration with poroelastic (task 2) and seismic (task 5) modeling indicated a 3rd set of faults **might** be present (neither identifiable from surface seismic or induced seismicity
- Rigorous study of tectonic actions that caused regional and local structural features that might have caused faults at IBDP. Concluded that tectonics **unlikely** to create other IBDP faults set

Regional (multi-state) structural features

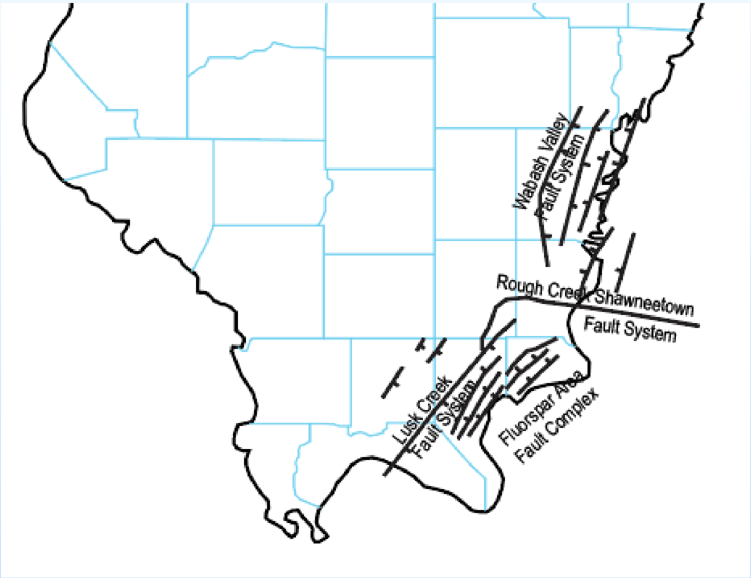


Illinois (local)structural features

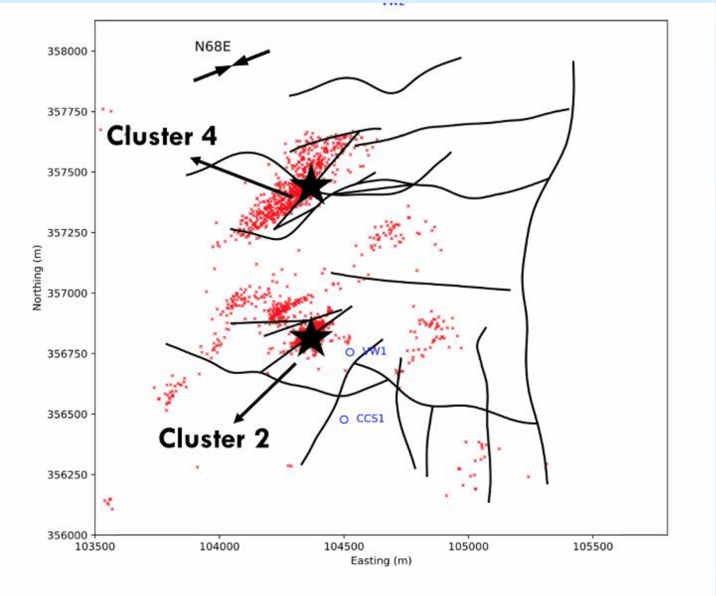


Technical Status: Task 2
Geologic Conceptual Modeling

- Study of regional tectonics revealed that Pennsylvanian age structural features had similar orientation as the trends of measured microseismic events
- Most recent geologic age structural activity may have caused the faults inferred through locations of microseismic measurement



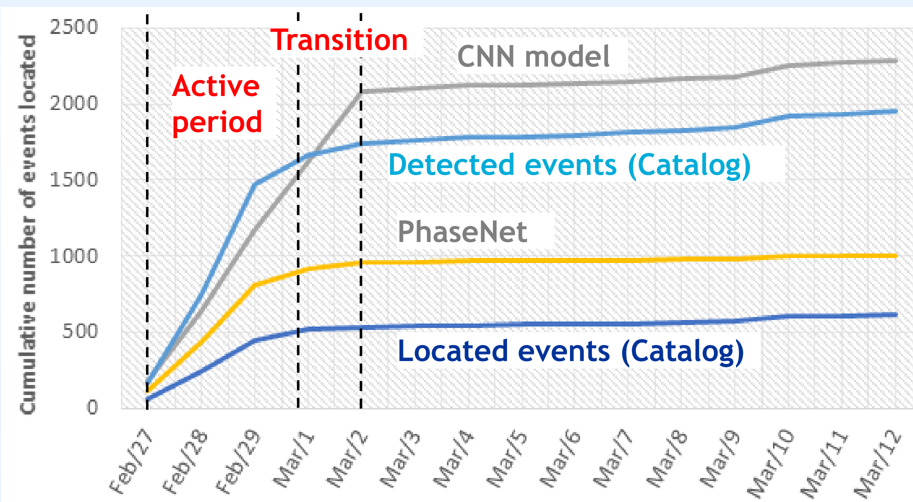
Illinois structural features during Pennsylvanian.



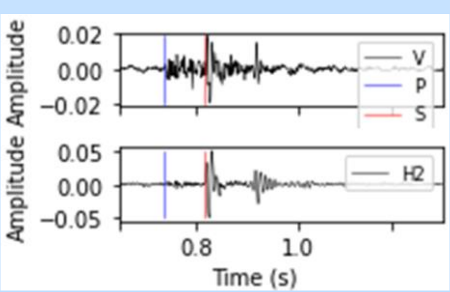
Faults from conventional methods, seismic, and located MS events, plus those from ML methods

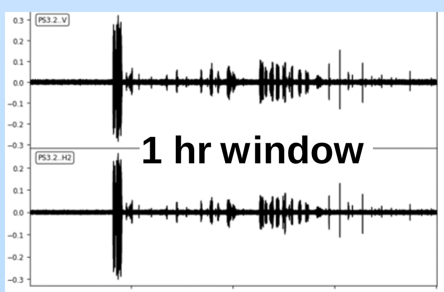
Technical Status: Task 3
Machine Learning

- Improved detection of seismic events and phase picking of p-/s-waves from cont. raw waveform data
  - Discovered long-period long-duration events



- Rescaled spectrograms as input to ML model dramatically improved CNN-based with more events per cluster and slow slip waveform patterns
- Retrained PhaseNet, estimated P- and S-arrival times more accurately
- Newly detected events during post-active period show long-period long-duration events to indicate that the fault associated with MS cluster #2 may have thick damaged zone and/or fractured networks

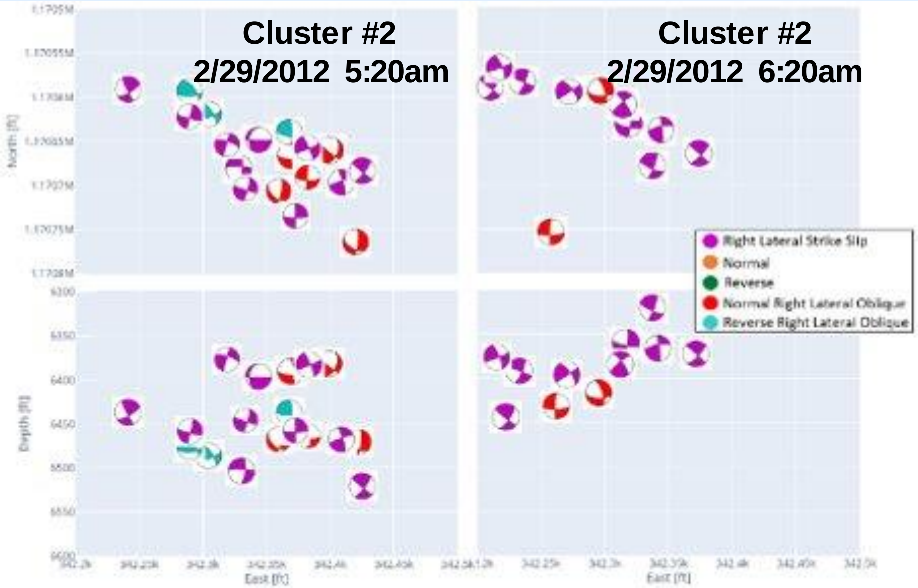


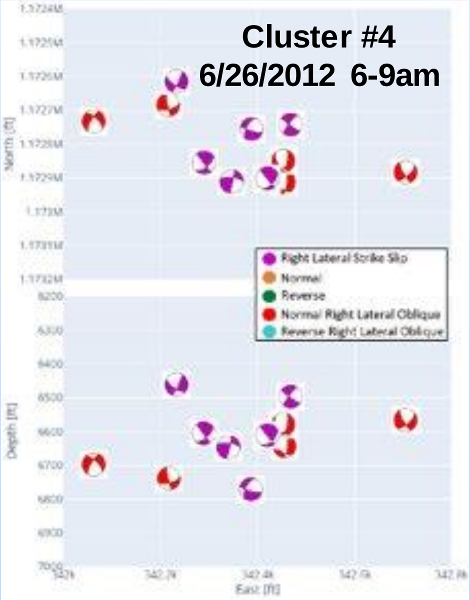


Top: Comparison of event-detection ML models for raw cont. waveform data w/located catalog events (Feb 27 to Mar 12, 2012.
Bottom, left: p- and s-wave arrival time of newly detected waveform data using PhaseNet.
Bottom, right: example of long-period long-duration seismic events during post-active period

Technical Status: Task 3 Microseismic Mechanisms

- Constructed fault planes from microseismic events using the spatio-temporal analysis of seismic events, statistical three-point method, and machine learning methods.
- Applied focal mechanism analysis tool (e.g., USGS HASH) based on the first motion and p- and s-wave magnitude ratio for selected events from unsupervised machine learning clustering.
- MS events reveals the sub-scale characteristics of slip patterns during active seismic periods within the fault architecture, which matches focal mechanism analysis results
- Focal mechanism analysis of unsupervised ML locate events have two major slip mechanisms: right lateral strike slip and (normal/reverse) right lateral oblique

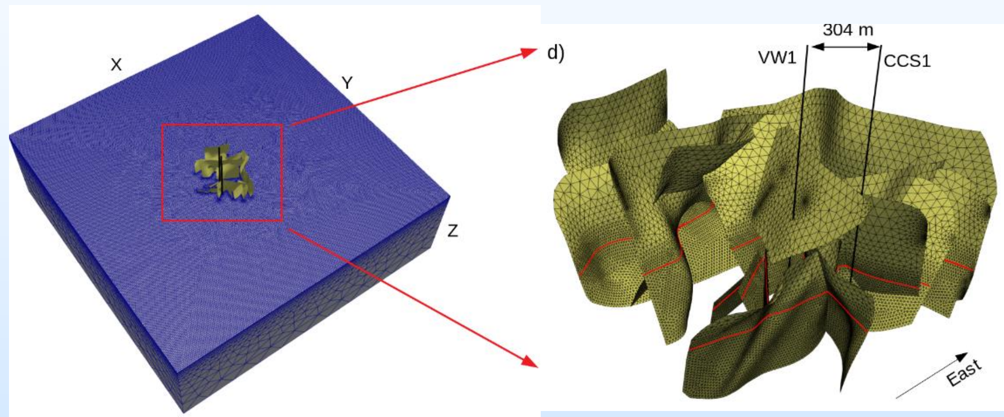


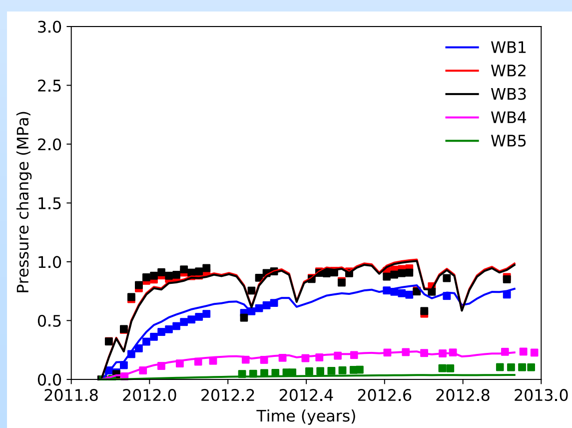


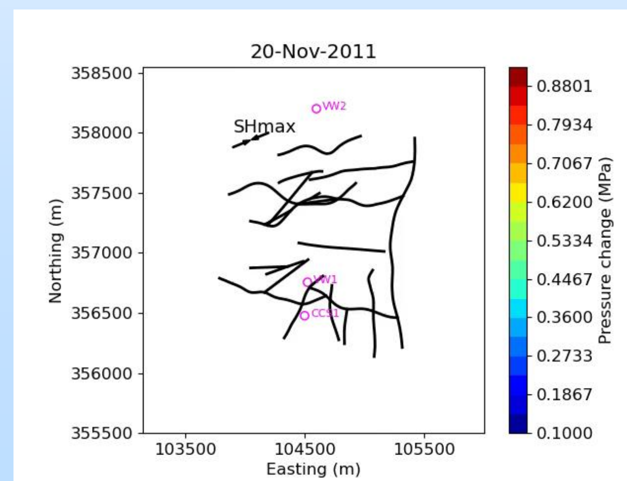
Example trend of MS events from cluster #2 (left) and #4 (right). Focal mechanisms from USGS HASH software. Most events have steep dip angles with right lateral strike slip and right lateral oblique.

Technical Status: Task 4
Flow-Geomechanics Modeling

- Built a computational flow-geomechanics model, with 3D unstructured mesh adapting to all horizons and all faults interpreted from 3D seismic (Task 2) and microseismicity analysis (Task 3)
- Geologic model calibration identified fault properties that led to favorable comparison of predicted and IBDP pressures and CO_2 saturations
- Along fault perm mostly influenced pressure; across fault perm mostly influenced CO_2 saturation
- Pore pressure initially confined to regions near the faults, then diffuses into fractured basement



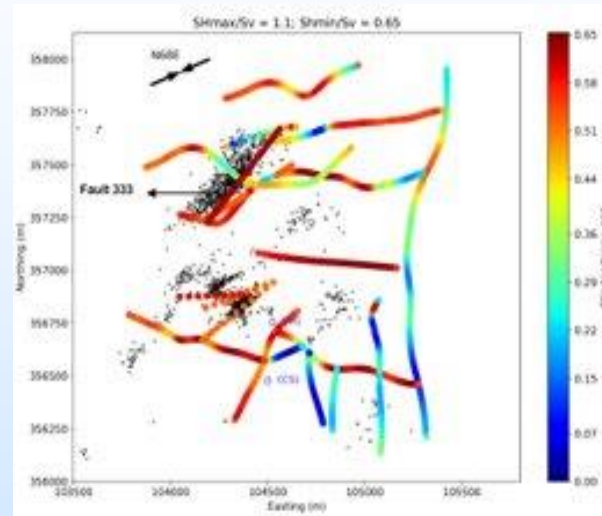




Technical Status: Task 4
Flow-Geomechanics Modeling

- Assessed fault proximity (in time) to failure (slip tendency) and changes in Coulomb Failure Function (DCFF) vs. time
  - Faults (friction) near the main clusters of seismicity are initially close to failure (0.6, Byerlee friction), with slip tendency ~0.55 – 0.65
  - Pore pressure increase due to CO_2 injection process **destabilizes** the basement faults
  - Stress changes from poroelastic effects are **small** and tend to **stabilize** the faults

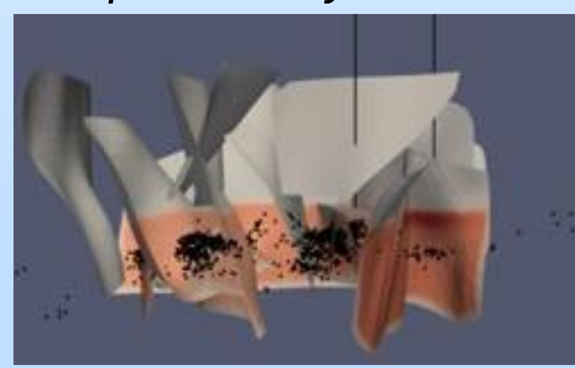
Slip tendency: top of basement



Slip tendency: 3D view

Lower Mt. Simon

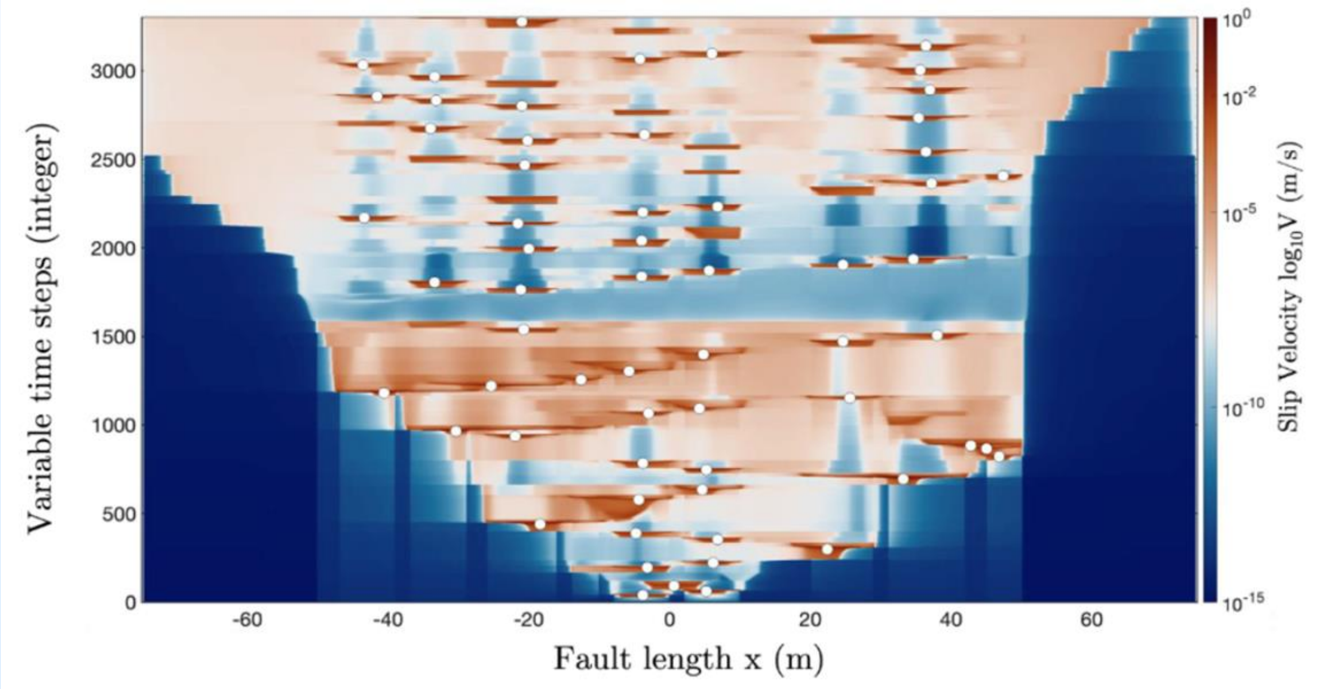
Basement



Technical Status: Task 5
Stress Field (Mechanical Modeling)

- Spatio-temporal evolution of slip rate on fault surface via pressure perturbation from injection
- Fluid is injected, fault zone pore pressure increases, the fault starts to slip.
- Induced events are generally small and arrested due to the frictional heterogeneity along fault.
- Some events grow bigger and penetrate through the creeping patches on the fault.
- Nucleation sites (white dots) are spatially distributed over the fault length
- Inter-event times are also non-uniform.

Frictional heterogeneity represented by velocity weaking and velocity strengthening properties. Creeping occurs in velocity strengthening regions

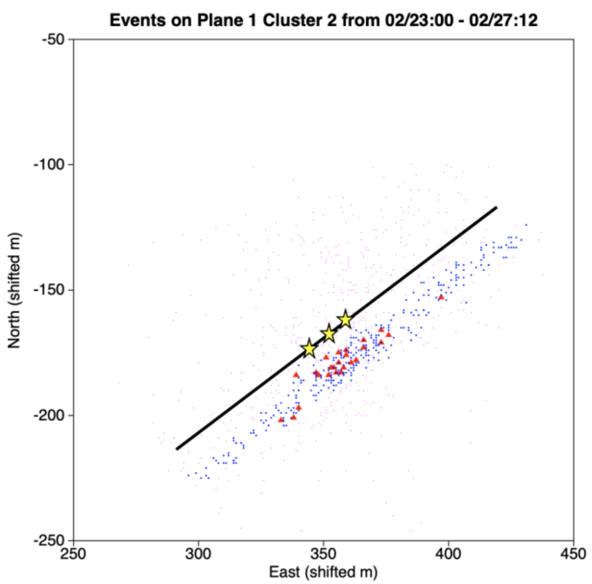


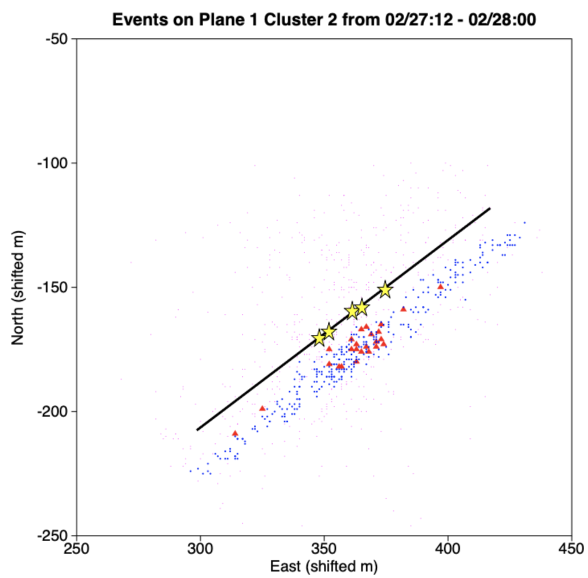
Pore pressure from poroelastic modeling, (task 4)

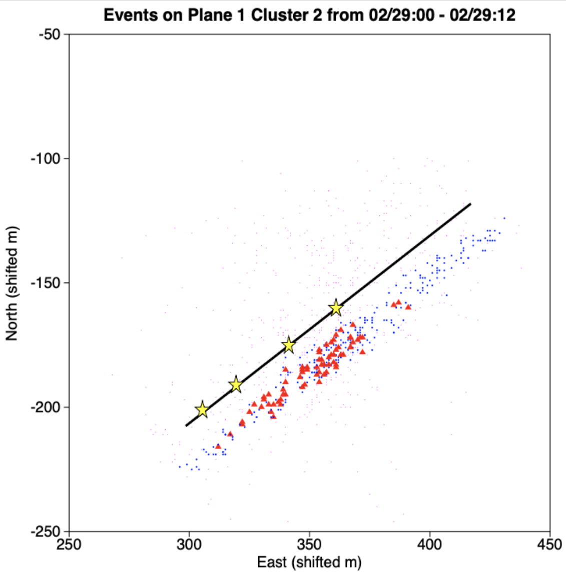
Example: Complex seismicity pattern similar to cluster 2

Technical Status: Task 5
Stress Field (Mechanical Modeling)

- Example of model generated seismicity compared to observed seismicity at different times.
- Varying frictional properties along the fault surface gave best match of IBDP Cluster 2 data







Blue-all recorded IBDP MS events of cluster 2; red- IBDP MS events during simulated time period; yellow-starts simulated MS events. Line is shifted from data for graphic purpose only.

Project Summary-Lessons Learned

Geologic and Geocellular Modeling

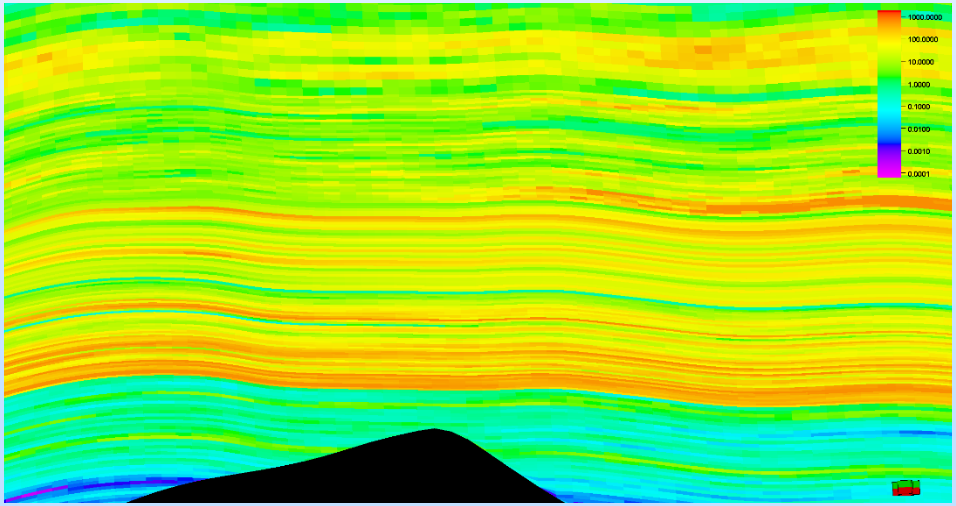
- small geologic features (e.g. low permeable layers) that tend to be average out of upscaled models, are necessary for rigorous model calibration of closely spaced wells
- Rigorous study and analyses of all regional structural features, emphasizing most recent features, should be used to infer faults present at an injection site

Machine Learning

- Improved detection and phase picking of MS data is the first automatic step for rapid recognition of (hidden) fault presence from MS data

Flow geomechanics modeling:

- Stress changes from poroelastic effects are small and tend to *stabilize the faults*
- Pore pressure diffusion to basement faults is main mechanism to *destabilize faults*



Vertical cross-section of lower Mt. Simon

Project Summary-Key Findings

Key Findings

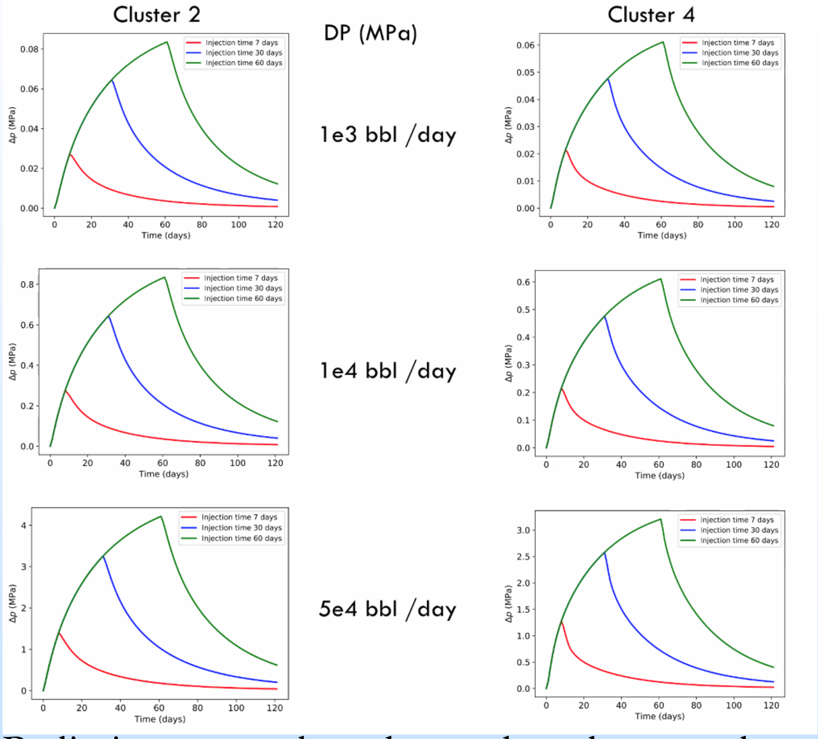
- Faults-identified with traditional interpretation of active (surface) seismic data, had *no to little* associated *induced seismicity*
- Faults, presumably the source of induced seismicity, were *not identifiable* from traditional interpretation of active (surface seismic data)
- Analyses of regional tectonic inferred faults present where microseismicity occurred.
- MS events reveals the sub-scale characteristics of slip patterns during active seismic periods within the fault architecture, which matches focal mechanism analysis results

Key Findings, contd.

- Poroelastic stress alone *cannot be responsible* for *seismicity*; it is more stabilizing because of fault properties and pore pressure
- Off-fault damage accumulates during seismic and aseismic slip and enables clustering of events over a hierarchy of time/space scales.
- Cluster 2's spatio-temporal distribution of injection-induced events reproduced in a fault model with heterogeneous frictional properties.
- Fault in weak fault zones (low yield strength) have smaller earthquakes. Faults in stronger fault zones have through-going events.
- Faults w/high shear to normal stress *more* susceptible to injection-induced seismicity. However, the size of events depend on the heterogeneous distribution of fault friction and the strength of fault zone.

Project Summary
Next (Final) Project Steps

- Using the calibrated models
  - Validate injection test method to test for induced seismicity as part of site screening
  - Test sensitivity of workflow to predict larger induced seismic events with calibrated model under different injection scenarios.
- Add to workflow: regional structural features review to compliment faults detected from traditional methods.

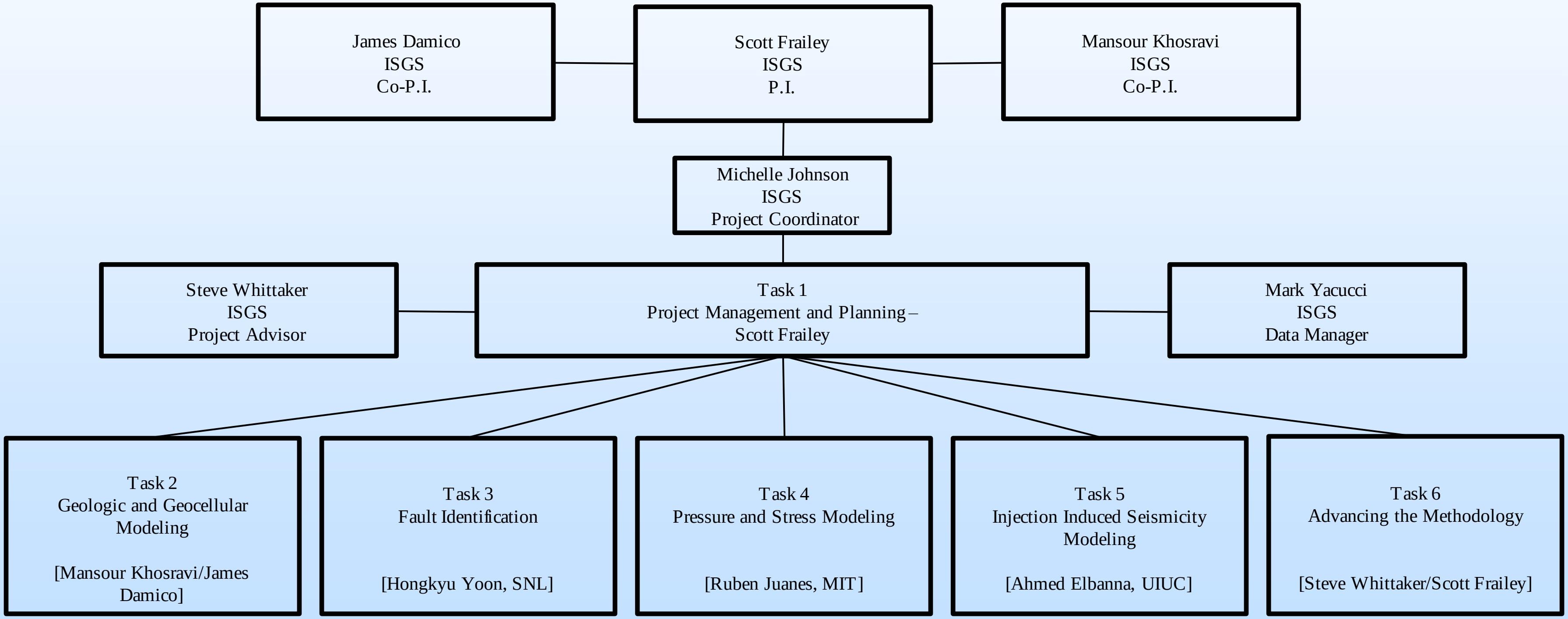


Preliminary results show that large volume (1000s bbls), short term (weeks) might induce microseismicity that can be used to calibrate a model using workflow in this project to assess the occurrence of larger injection induced seismicity.

Appendix

- Organization chart
- Gantt chart

Appendix: Organization Chart



Appendix: Gantt Chart

	Project Year	Y1				Y2				Y3				Y4				Y5
	Project Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
	Calendar year	2018	2019				2020				2021				2022			2022
	Calendar quarter	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Task	Responsible Party																	
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, Monroe																	
1.3 – Annual DOE reports and meetings	Task Leaders, Johnson, Monroe																	
Milestone: Project Management Plan	Frailey & Johnson	100%																
Task 2.0 – Geologic and Geocellular Modeling																		
2.1 – Comprehensive review of existing models	Kosravi	100%																
2.2 – Conceptual geologic models of storage unit and crystalline	Kosravi	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	100%																
2.4 –Geocellular representation of the conceptual geologic model based on characterization data	Kosravi	100%																
Subtask 2.5 – Geologic and geocellular model realizations based on forward and inverse stress and pressure modeling	Khosravi	100%																
Milestone: Initial geocellular models	Khosravi	100%																
Milestone: Update of geocellular models with *(Task 3)* faults	Khosravi	100%																
Task 3.0 – Fault Identification	Yoon & MIT																	
3.1 – Detection of microseismic events	Yoon & MIT	100%																
3.2 – Characteristics of microseismic events	Yoon & MIT	100%																
3.3–Bayesian inversion* of time-lapse microseismicity data into coupled flow-geomechanics models	MIT	80%																
3.4 - Rapid recognition of the presence of (undetected) faults and fault interactions using deep learning approach	Yoon	80%																
Milestone: Initial assessment of fault locations	Yoon & MIT	100%																
Go/No-Go Point 1 - Identification of Faults via multivariate inverse	Yoon & MIT																	
Milestone: Validate fault model with seismic data/conceptual	Yoon & MIT	90%																
Go/No-Go Point 2 - Identification of Faults via machine learning	Yoon & MIT																	
Task 4.0 – Pressure and Stress Modeling																		
4.1 – Pressure perturbation	Frailey	100%																
4.2 – Fracture flow	Juanes	100%																
4.3 – Stress perturbation	Juanes & Frailey	90%																
Milestone: Initial model of pressure and stress	Juanes	100%																
Task 5.0 – Injection Induced Seismicity Modeling																		
5.1 – Curation of input data and model output	Elbana	100%																
5.2 – Fault slip modeling	Elbana	100%																
Go/No-Go Point 3 - Fault slippage via seismicity modeling	Elbana																	
5.3 – System level seismicity modeling	Elbana	80%																
5.4 – Development of conceptual model for induced seismicity	Elbana	80%																
5.5 – Model Validation and updating	Elbana	80%																
Task 6.0 – Advancing the Methodology																		
6.1 – Field site calibration	Task Leaders	100%																
6.2 – Improvement over current state-of-the-art to identify faults	Task Leaders	0%																
Milestone: Summary of findings	Task Leaders, Johnson, Monroe	25%																