Machine Learning and Seismology for Real-Time Decision-Making in Stimulation

1. **Cutting-edge application of machine learning, geomechanics, and seismology for real-time decision-making tools during stimulation**
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   - Subcontractors and/or Participating Organizations: University of California Berkeley
   - Project Start and End Date: 4/2024-3/2027

2. **Project Objectives and Purpose**

Major technical objectives of the project

2.1 Development of a Real-Time Decision-Making Platform
- Data Analysis and Seismic Event Detection.
- Moment Magnitude Calculations.
- Maximum Magnitude Prediction.

2.2. Seismo-Geomechanical Characterization
- Site Characterization.
- Velocity and Geomechanical Models.

2.3. Compliance Technology for Real-Time Data Acquisition
- Data Pipeline Development.
- Server Deployment.

2.4. Risk Assessment and Management Tools
- Geomechanical and Seismological Models.
- Red-Light Shut-In Tool.
- Ground Motion Prediction.
- Nuisance and Fragility Functions.

2.5. Real-Time Simulation and Tool Validation
- Model Calibration and Testing.
- Real-Time Simulations.

The impact of our research and development
- The project contributes to making geothermal energy a more reliable, safe, and efficient renewable energy source, thereby supporting its broader adoption and deployment worldwide.
- Immediate Response
- Improved Safety
- Data-Driven Decisions
- Proactive Risk Mitigation
- Enhanced Prediction Models
- Community Safety
- Infrastructure Protection
- Reduction of Seismic Risks
- Optimization of Geothermal Operations
- Support for Policy and Regulatory Frameworks

Year 2 Objectives, Milestones, and Overall Progress

Technical area	Year 2 objective	Current status	Major Year 2 outcome
Seismic monitoring	Complete and validate catalogs	Completed	Multiple independent catalogs generated and compared
Geomechanical risk	Complete fault-slip assessment	Completed	Fault extraction + slip-potential workflow
Hazard prediction	Complete nuisance/fragility models	Developed	Spatially explicit impact assessment
System integration	Integrate modules	Completed / demonstrated	Server-based workflow demonstrated on FORGE data
Real-time validation	Replay stimulation data	Demonstrated	End-to-end processing evaluated

3. Technical Barriers and Targets

The project addresses the challenge of turning large and diverse seismic datasets into information that can support decisions during geothermal stimulation. DAS, downhole geophones, and surface stations provide complementary observations, but they differ in sensitivity, resolution, data volume, and processing requirements. This makes automated event detection, location, and integration into a consistent seismic catalog challenging, particularly when results are needed rapidly.

Another challenge is moving from detecting seismic events to assessing their risk. Event locations must be translated into active fault geometries, fault slip potential, and the evolution of rupture with time. To address this, we developed workflows for clustering seismicity, fitting fault planes, and evaluating fault stability. We also developed three complementary indicators for detecting potential runaway rupture based on rupture-front propagation, seismic-moment acceleration, and the coupling between rupture propagation and seismic energy release. Testing against three independent FORGE catalogs showed differences between the catalogs but a consistent interpretation of stable rupture behavior.

A further challenge is translating seismicity into quantities that are directly relevant to operational decisions and nearby communities. The project therefore connects seismic monitoring with maximum-magnitude and ground-motion prediction and with nuisance and damage assessment. The fragility analysis incorporates earthquake location and magnitude, site conditions, and population exposure to estimate spatially varying impacts.

Finally, integrating these individual components into a single near-real-time workflow remains an important technical challenge. The project has progressed from developing individual algorithms toward testing an integrated server-based workflow using historical FORGE stimulation data as a proxy for real-time operation.

Technical Targets and Accomplishments

Technical Target	Accomplishment
Seismic detection and location	Automated ML-based event detection, association, and location workflows developed and tested.
DAS monitoring	Picking-free DAS source-imaging workflow and event catalog developed.
Multi-sensor integration	DAS, geophone, and surface-station catalogs generated and compared.
Hazard prediction	Maximum-magnitude and ground-motion models developed and tested.
Rupture behavior	Three rupture diagnostics developed and tested across multiple catalogs.
Impact assessment	Nuisance and fragility models developed using ground motion, site conditions, and exposure.
Real-time integration	Processing modules integrated and tested in a server-based workflow.

4. Technical Approach

The project uses an integrated seismology–machine learning–geomechanics workflow to convert continuous seismic observations into information that can support operational decisions during geothermal stimulation. The approach progresses from data acquisition and seismic event detection, through event location and fault characterization, to geomechanical and seismic hazard assessment, and ultimately to Traffic Light System (TLS) decision support.

The technical approach consists of five connected components:

1. **Multi-sensor seismic monitoring:** DAS, downhole geophones, and surface seismic stations are processed using complementary picking-based and picking-free source-imaging methods to detect and locate microseismic events.
2. **Automated catalog and fault characterization:** Machine-learning and statistical methods are used for phase picking, association, event location, clustering, and fault-plane identification.
3. **Geomechanical risk assessment**: Identified structures are evaluated against the reservoir stress and pressure conditions to estimate fault slip potential.
4. **Dynamic hazard assessment:** Maximum magnitude, ground motion, rupture propagation, nuisance, and structural fragility are evaluated as the seismic sequence evolves.
5. **Integrated processing and decision support**: The individual modules are connected in a server-based workflow and tested using FORGE stimulation data as a proxy for near-real-time operation.

Key issues we are currently working on include differences between seismic catalogs, uncertainty in event locations and fault characterization, processing time, and integration of the different tools into a near-real-time workflow. These issues matter because uncertainty in seismic analysis can carry through to fault identification, slip-potential estimates, and ultimately operational decisions. Rather than relying on a single seismic catalog or a simple magnitude threshold, our approach combines complementary picking-based and picking-free methods with geomechanical and hazard analysis. We are also developing multiple indicators to identify possible runaway rupture and link the seismic results to expected ground motion, nuisance, and damage.

5. Project Timeline

Milestone / Decision Point	Date
Project start	April 2024
Site characterization and adjacent-area characterization completed	August 2025
Data pipeline, FORGE/UofU server, and data-acquisition pilot completed	August 2025
Geomechanical risk model and seismic catalogs completed	August 2025
Maximum-magnitude prediction completed	August 2025
Year 1 Go/No-Go decision – Passed	2025
Ground-motion, nuisance, and fragility models completed	August 2026
Runaway-rupture diagnostics developed and tested	August 2026
Model validation using FORGE stimulation data completed	August 2026
Year 2 Go/No-Go decision – Passed	2026
Real-time simulation demo using FORGE stimulation data completed	August 2026
Nuisance/damage impact and full module assembly	Expected December 2026
Final rupture-model refinement	Expected March 2027

6. Technical Accomplishments

During Year 2, the project progressed from developing individual monitoring and risk-analysis components toward testing and integrating them into a near-real-time seismic monitoring and decision-support workflow. Major accomplishments included completing and comparing multiple seismic catalogs, improving fault characterization and slip-potential assessment, developing quantitative runaway-rupture diagnostics, advancing ground-motion and impact models, and demonstrating the integrated workflow using FORGE stimulation data.

6.1 Seismic Monitoring and Catalog Development

We developed and tested automated seismic processing workflows using data from April 2024 FORGE stimulation (Fig. 1). The workflow combines machine-learning-based phase picking, association, and event location with complementary waveform-based source imaging using DAS and downhole geophone observations. We generated multiple catalogs using different sensor combinations and processing approaches, providing independent datasets to evaluate seismicity evolution and fault activation (Fig. 2). The picking-based workflow produced 2,948 relocated events, while the waveform-based workflow initially located 2,680 events, of which 2,338 remained after quality control.

A key accomplishment this year was moving beyond catalog generation to comparing spatial and temporal behavior and evaluating how catalog differences affect downstream interpretation. This matters because uncertainty in event locations can influence clustering, inferred fault geometry, and geomechanical risk calculations.

6.2 Fault Characterization and Geomechanical Risk Assessment

The seismic catalogs were integrated with automated spatial clustering and fault-plane fitting to identify structures activated during stimulation. The resulting fault geometries were evaluated using the site stress conditions and Mohr–Coulomb failure analysis to estimate fault slip potential (Fig. 3).

This provides an important connection between seismic monitoring and operational risk assessment: instead of treating each earthquake independently, the workflow evaluates whether groups of events represent activation and growth of potentially unstable structures.

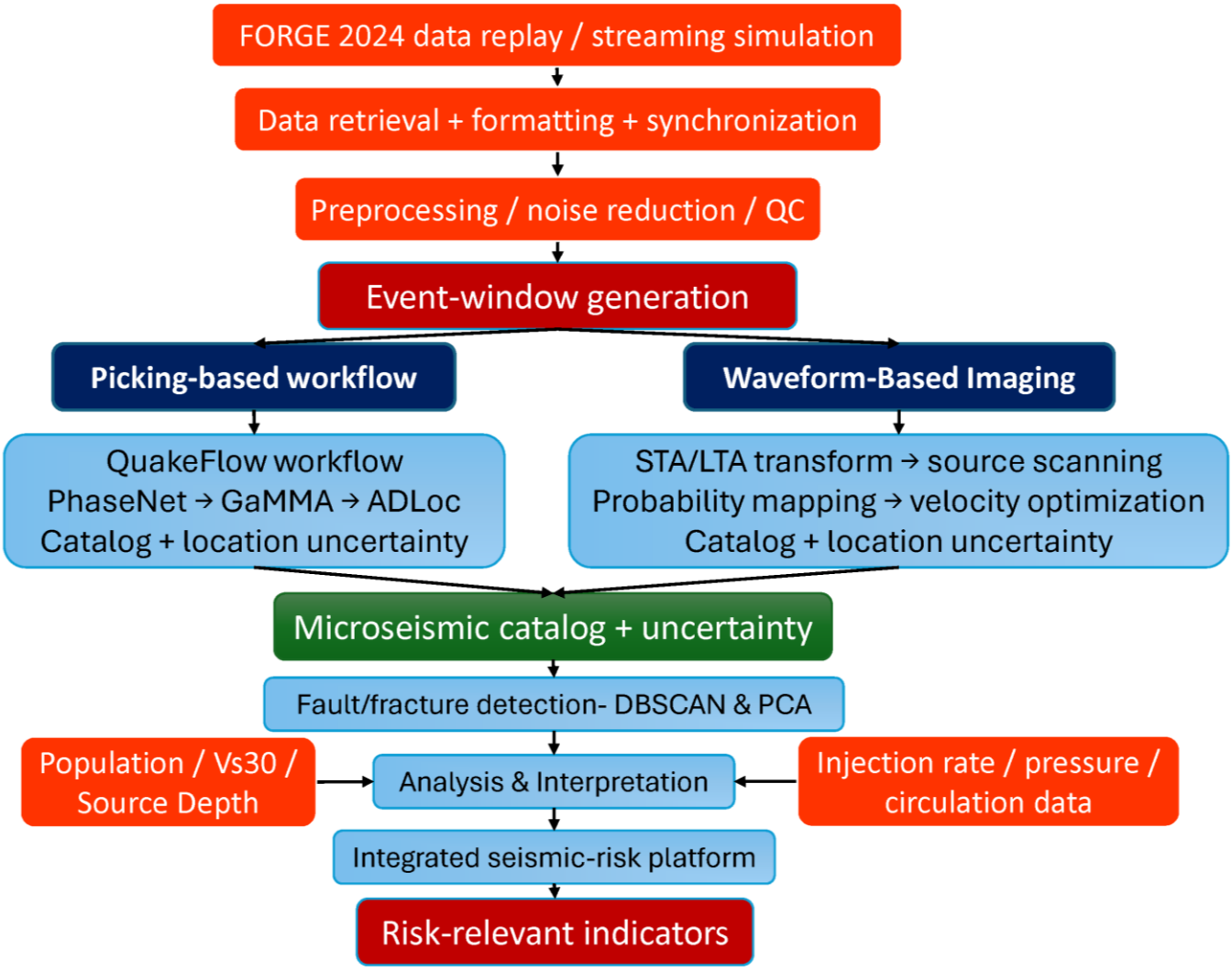


Figure 1. Integrated near-real-time seismic monitoring and risk-assessment workflow for FORGE stimulation data.

6.3 Rupture Diagnostics

A major Year 2 accomplishment was developing and testing quantitative indicators to identify rupture processes. We evaluated three complementary criteria: rupture-front propagation, acceleration of cumulative seismic moment, and coupling between seismic moment release and rupture-front propagation.

We tested the approach independently using the GES Multi-Sensor, DAS-Relocated, and Integrated AI-Based catalogs (Fig. 4). Although the catalogs differ in spatial distribution and rupture evolution, none showed sustained super-diffusive propagation with persistent energetic acceleration. The three analyses therefore produced a consistent interpretation of stable rather than runaway rupture behavior for the evaluated FORGE stimulation.

This represents an important advance toward the project's red-light objective because the analysis considers how a seismic sequence is evolving, rather than relying only on whether an individual event exceeds a predefined magnitude threshold.

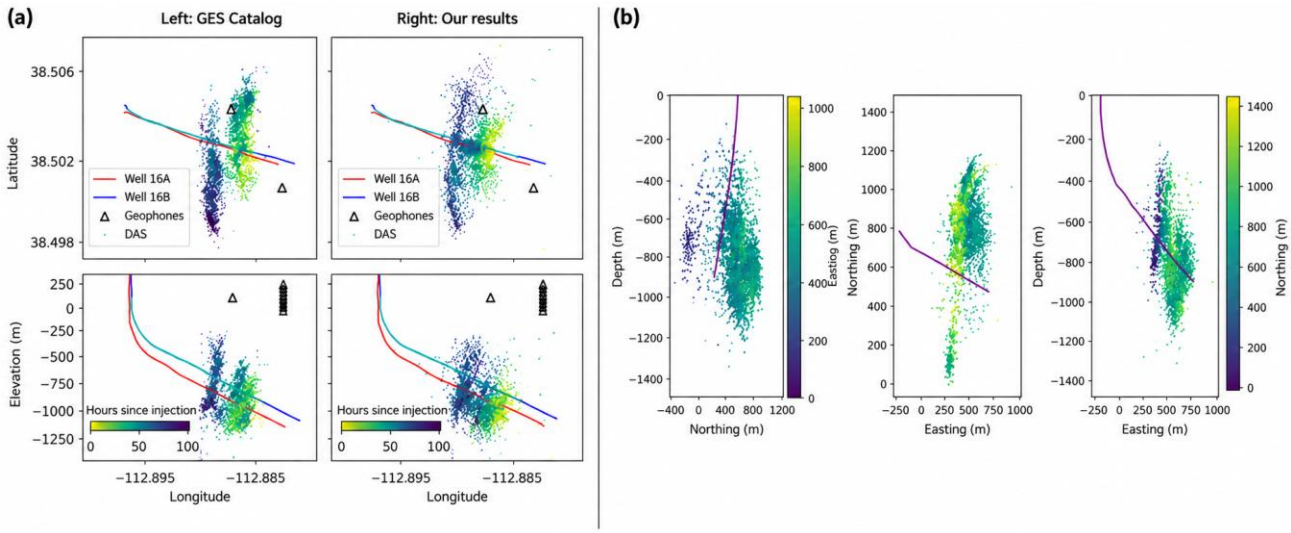


Figure 2. Comparison of the two seismic catalog-generation approaches. (a) Picking-based workflow results compared with the GES catalog, resulting in 2,948 relocated events. (b) Waveform-based source-imaging results using DAS and geophone data; 2,680 events were initially located and 2,338 events remained after quality control.

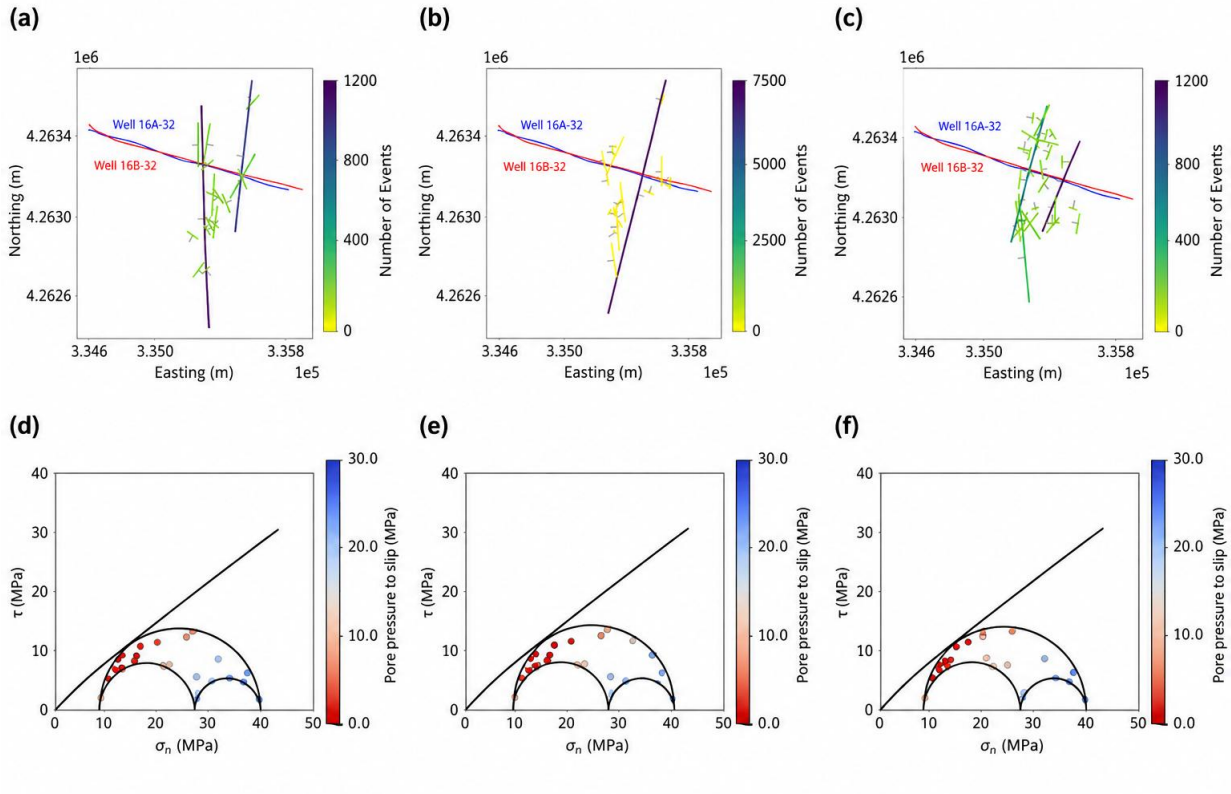


Figure 3. Multi-catalog fault characterization and geomechanical slip-potential assessment. (a–c) Fault structures identified using DBSCAN clustering and PCA-based fault-plane fitting for the GES Multi-Sensor, DAS-Relocated, and Integrated AI-Based seismic catalogs, respectively. (d–f) Corresponding Mohr–Coulomb fault-slip-potential assessment, expressed in terms of the pore-pressure increase required for reactivation. Applying the same analysis to independent seismic catalogs provides a measure of the robustness of the inferred fault structures and associated geomechanical risk.

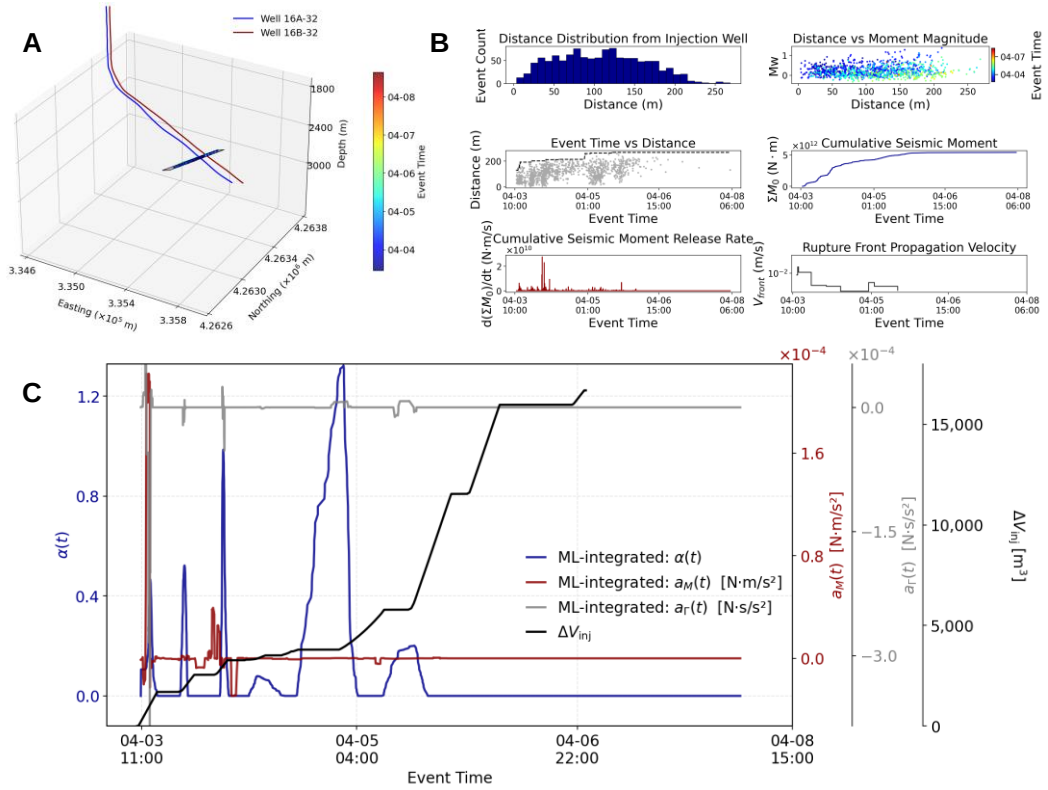


Figure 4. Rupture-behavior assessment using the Integrated AI-Based seismic catalog. Rupture propagation and seismic-energy evolution were evaluated using three complementary diagnostics: rupture-front propagation, seismic-moment acceleration, and energy–propagation coupling. The catalog shows an initial period of rapid propagation followed by stabilization, with decreasing rupture-front velocity and no sustained energetic acceleration. Overall, the analysis indicates stable rather than runaway rupture behavior. Independent analyses of the GES Multi-Sensor and DAS-Relocated catalogs produced the same overall interpretation.

6.4 Ground Motion, Nuisance, and Fragility Assessment

The hazard workflow was expanded to translate subsurface seismicity into potential surface impacts. The framework combines earthquake magnitude and location with ground-motion prediction, spatially variable V_{S30}, and population exposure to estimate nuisance and potential structural damage.

Ground-motion scenarios were evaluated across the FORGE region. For example, a M_w 1.85 event located at the injection zone produces PGA and PGV that decrease rapidly with distance from the source, with predicted motions at Milford, Minersville, and Beaver remaining well below perception thresholds (Fig. 5).

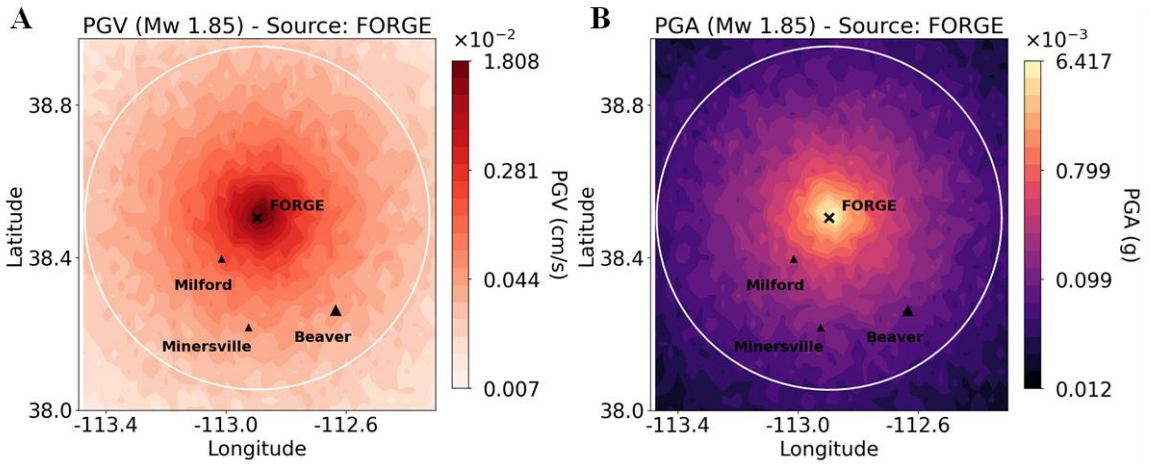


Figure 5. Predicted spatial distribution of ground motion for a M_w 1.85 event at the FORGE injection zone. (a) Peak ground velocity (PGV) and (b) peak ground acceleration (PGA) show radial decay away from the source. Predicted ground motions at Milford, Minersville, and Beaver remain well below perception thresholds for this scenario (PGV < 0.1 cm/s and PGA < 0.001 g).

6.5 Integrated Workflow and Validation

The individual monitoring, geomechanical, rupture-diagnostic, and hazard modules were integrated into a unified processing framework. Historical FORGE stimulation data were used as a proxy for incoming real-time data to test the workflow from seismic processing through event catalog generation, fault characterization, rupture assessment, and hazard evaluation (Fig. 1).

This represents a significant project milestone because it moves the work from development of individual algorithms toward an end-to-end decision-support system. The Year 2 Go/No-Go decision was passed, and the project is now focused on further integration, computational efficiency, uncertainty characterization, and preparation for application during future stimulation operations.

7. Challenges to Date

The project has remained generally on schedule, with both the Year 1 and Year 2 Go/No-Go milestones successfully passed. The main challenges have been technical rather than major changes to the project scope. One important challenge has been integrating large and diverse datasets from DAS, downhole geophones, and other seismic monitoring systems into a common near-real-time workflow. Differences in sensor geometry, data quality, timing, and event-location results can propagate into fault characterization and subsequent risk assessment.

Another challenge has been moving from individual algorithms to an integrated and sufficiently automated workflow. DAS processing in particular is computationally demanding, and some processing and quality-control steps still require supervision. Historical FORGE stimulation data have therefore been replayed as a proxy for streaming data to test the complete processing chain, identify bottlenecks, and improve automation before future real-time deployment.

Differences among seismic catalogs and uncertainty in event locations have also required additional evaluation. Rather than relying on a single catalog, the project uses complementary picking-based and waveform-based approaches and compares results across independent catalogs. The same strategy was used for the runaway-rupture

analysis, where three independent catalogs were evaluated using multiple diagnostic criteria. Despite differences among the catalogs, the analyses produced a consistent interpretation of stable rupture behavior.

No major change in the overall technical objectives has been required. Remaining work focuses on improving computational efficiency, uncertainty characterization, integration of the hazard modules, and documenting which components can operate automatically versus those that still require supervision.

8. Conclusion and Plans for the Future

The project has made substantial progress toward an integrated, near-real-time seismic monitoring and risk-assessment framework for geothermal stimulation. The major monitoring, catalog-generation, fault-characterization, geomechanical, runaway-rupture, and hazard-assessment components have been developed and tested using FORGE stimulation data. Importantly, the project has progressed from developing individual tools to integrating them into a common workflow that connects seismic observations with risk-relevant information for Traffic Light System decisions.

During the final project period, the focus will shift toward completing the integration and validation of the full workflow, including nuisance and damage assessment, computational optimization, and improved treatment of uncertainty. Additional effort will be directed toward testing automation and processing efficiency, documenting the workflow and its limitations, and preparing project data and results for dissemination. The overall goal is to leave a validated and transferable framework that can support seismic monitoring and risk management during future FORGE and other geothermal stimulation operations.

9. Geothermal Data Repository

The project has made data and products publicly available through the Geothermal Data Repository (GDR). The following project-related datasets and products have been uploaded:

GDR Submission	Date
Utah FORGE: Source Imaging DAS-Based Seismic Event Catalog – April 2024 Stimulation	August 2025
Utah FORGE: Phase-Picking Based Microseismic Event Catalog – April 2024 Stimulation	February 2026

10. Publications and Presentations, Intellectual Property (IP), Licenses, etc.

The project has resulted in peer-reviewed conference papers, technical presentations, public seismic catalogs, graduate research, and manuscripts currently in development. No patents or commercial licenses have resulted from the project to date.

Publications and Conference Proceedings

1. Zhang, X., Zhu, W., Salvage, R. O., and Dvory, N. Z. (2025). “Deep Neural Network-Based Workflow for Accurate Seismic Catalog Generation from Low Resolution Seismic Data in Enhanced Geothermal System Operations.” Proceedings, 50th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.
2. Zhang, X. M., and Dvory, N. Z. (2025). “Estimating Fault Slip Potential with CNN-Based Deep Learning: Integrating Mohr-Coulomb and Non-Linear Failure Criteria for Advanced Seismic Risk Assessment.” 59th U.S. Rock Mechanics/Geomechanics Symposium, ARMA-2025-0408. DOI: 10.56952/ARMA-2025-0408.
3. Zhang, X., Shimony, E., Song, J., Wygodny, U., Zhu, W., Lellouch, A., and Dvory, N. Z. (2026). “Microseismic Location in EGS: Comparing Picking-Based and Source-Imaging Workflows on Downhole DAS Data.” Proceedings, 51st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-230.
4. Zhang, X., and Dvory, N. Z. (2026). “Integration of Maximum Magnitude Forecast and Ground Motion Prediction for Real-Time Seismic Hazard Assessment at Utah FORGE.” Proceedings, 51st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-230.

5. Zhang, X., Shimony, E., Wygodny, U., Lellouch, A., and Dvory, N. Z. (2026). "Fault Identification Using Multiple Event Catalogs from the Stimulation Operation at the Utah FORGE Site." 60th U.S. Rock Mechanics/Geomechanics Symposium, Tucson, Arizona, June 2026.

Manuscript under review

1. Zhang, X., Schultz, R., and Dvory, N. Z. (2026). Work associated with "Real-Time Forecasting of Maximum Induced-Earthquake Magnitude During EGS Stimulation: Insights from the Utah FORGE 2022 and 2024 Campaigns."

Graduate Research

1. Wygodny, U. (2026). M.Sc. thesis, Tel Aviv University, based in part on the hybrid DAS–geophone source-imaging and microseismic-location research conducted using the April 2024 Utah FORGE stimulation dataset. The thesis includes development and evaluation of the picking-free source-imaging workflow and comparison with other FORGE event-location results. Completed/2026.

Presentations and Workshops

1. Zhang, X., and Dvory, N. Z. (2025). "Integrated Deep Learning and Failure Criterion Approaches for Fault Slip Assessment in Enhanced Geothermal Systems." AGU Annual Meeting, 2025.
2. Shimony, E., Wygodny, U., Zhang, X., Dvory, N. Z., and Lellouch, A. (2025). "Picking-Free Microseismic Event Location with Downhole DAS and Geophones." AGU Annual Meeting, New Orleans, 2025. The work presented the hybrid source-imaging approach applied to approximately 3,000 events from the April 2024 FORGE stimulation.
3. Shimony, E., Wygodny, U., Zhang, X., Dvory, N. Z., and Lellouch, A. (2025). "Picking-Free Microseismic Event Location with Downhole DAS and Geophones." Israel Geological Society Annual Meeting, 2025.
4. Zhang, X., Shimony, E., Song, J., Wygodny, U., Zhu, W., Lellouch, A., and Dvory, N. Z. (2026). "Microseismic Location in EGS: Comparing Picking-Based and Source-Imaging Workflows on Downhole DAS Data." 51st Stanford Geothermal Workshop, February 9–11, 2026.
5. Zhang, X., and Dvory, N. Z. (2026). "Integration of Maximum Magnitude Forecast and Ground Motion Prediction for Real-Time Seismic Hazard Assessment at Utah FORGE." 51st Stanford Geothermal Workshop, February 9–11, 2026.
6. Zhang, X., Shimony, E., Wygodny, U., Lellouch, A., and Dvory, N. Z. (2026). "Fault Identification Using Multiple Event Catalogs from the Stimulation Operation at the Utah FORGE Site." 60th U.S. Rock Mechanics/Geomechanics Symposium, Tucson, Arizona, June 2026.
7. Zhang, X., Schultz, R., and Dvory, N. Z. (2026). "Real-Time Forecasting of Maximum Induced-Earthquake Magnitude During EGS Stimulation: Insights from the Utah FORGE 2022 and 2024 Campaigns." AGU Annual Meeting, 2026.

11. Publicity and Outreach

Project results have been shared through public datasets, scientific workshops, and organized conference sessions aimed at reaching the broader geothermal and geoscience communities. Project seismic catalogs and supporting data have been released through the DOE Geothermal Data Repository (GDR), allowing the results to be used beyond the project team.

The project has also supported broader community engagement on induced-seismicity risk and geothermal reservoir monitoring. The PI developed and co-led the "Seismic Risk and Reservoir Integrity in EGS: Mechanisms, Monitoring, Mitigation" workshop at the 2025 Geothermal Rising Conference with Nori Nakata. The PI also led induced-seismicity sessions at the 2025 and 2026 AGU Fall Meetings, chaired the "Monitoring and Characterization in Geothermal Reservoirs" session at the 2026 ARMA Symposium, and is currently leading development of the Geothermal Track for the 2027 ARMA Symposium. These activities provide opportunities to share FORGE results and bring together researchers, operators, and other stakeholders working on seismic monitoring, reservoir characterization, and risk management in geothermal systems.