# Lessons Learned from Decades of Seismic Monitoring at Enhanced and Conventional Geothermal Fields

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## ABSTRACT

To meet the growing demand for Enhanced Geothermal Systems (EGS) deployment across the United States, it is essential to expand EGS viability across a wide range of geological settings that differ in lithology, temperature, stress regime, and fluid conditions. A key challenge in scaling EGS is the management of induced seismicity, which directly influences both public perception and long-term operational success.

At Lawrence Berkeley National Laboratory (LBNL), we have established and operated seismic monitoring systems across a diverse portfolio of EGS and conventional geothermal sites, including The Geysers, Desert Peak, Brady Hot Springs, Raft River, Newberry, Patua, Cape Modern and Utah FORGE geothermal fields. These networks—ranging from borehole and surface geophones to broadband optical accelerometers—were tailored to site-specific geological and operational conditions, enabling long-term, high-resolution observation of microseismic activity and reservoir behavior.

Drawing on more than a decade of multi-site experience, we present the principal lessons learned from field deployments and sustained monitoring. These lessons encompass network design trade-offs between cost, sensitivity, and spatial coverage; the critical role of borehole sensors in lowering magnitude completeness below M0.0; the benefits of robust telemetry and data streaming for real-time analysis; and the importance of calibration, permitting, and noise mitigation. Together, these insights have informed the development of best practices for seismic monitoring in EGS projects and contributed to DOE's evolving induced seismicity protocols.

Finally, we highlight LBNL's ongoing efforts to ensure open data access through repositories such as NSF SAGE, fostering collaboration and advancing future geothermal research and reservoir management.

## 1. INTRODUCTION

The U.S. Department of Energy (DOE) is investing in Enhanced Geothermal Systems (EGS) as a scalable, baseload renewable energy source to help meet the nation's decarbonization goals. EGS has the potential to unlock geothermal resources in areas without sufficient natural permeability, but its widespread deployment hinges on the ability to monitor and manage induced seismicity—both to mitigate operational risks and to gain public trust.

This paper summarizes Lawrence Berkeley National Laboratory's (LBNL) extensive seismic monitoring activities across a diverse set of geothermal sites, including EGS demonstrations and conventional fields. These include The Geysers, Brady Hot Springs, Desert Peak, Newberry, Raft River, Patua, Don A. Campbell, Jersey Valley, Utah FORGE, and Cape Modern. At each site, we have installed, operated, and maintained seismic networks tailored to site-specific geological and operational conditions. The networks vary in size and configuration—from borehole geophones and optical accelerometers to surface nodal arrays—and have evolved to improve detection thresholds and spatial resolution.

A major objective of our work is to support reservoir development and management by collecting high-quality microseismic data during stimulation and production. Beyond seismic hazard evaluation, these data provide insights into reservoir structure, stress state, and fracture behavior. At sites like Patua and Desert Peak, we have shown how dense monitoring arrays reduce the magnitude of completeness to below M0.0, enabling the detection of small events linked to localized fracture activation. These observations inform reservoir models and help validate injection strategies in real time.

Another focus of this work is to enhance real-time data processing and transmission. Recent deployments employ robust telemetry—including 3G/4G cellular and satellite communication—to stream high-frequency (≥1 kHz), three-component seismic data to central servers. This facilitates near-instantaneous detection, phase picking, and magnitude estimation through automated processing pipelines. At Jersey Valley and Don A. Campbell, we demonstrate that modern telemetry and adaptive protocols can overcome many limitations of legacy monitoring systems.

This paper also presents lessons learned from over a decade of site deployments. These include sensor installation practices, permitting and land access considerations, noise mitigation strategies, and recommendations for calibration and quality control. We discuss how trade-offs between borehole depth, array density, sensor type, and cost affect the performance of seismic networks. Additionally, we emphasize the growing importance of scalable and high-temperature-compatible sensors, especially for long-term monitoring near stimulation zones.

Ultimately, the goal of this work is to contribute to best practices for seismic monitoring of EGS projects, grounded in real-world deployment experience. By integrating engineering needs with scientific insight, and by openly sharing data and methods, we aim to help enable the safe, effective, and publicly acceptable expansion of geothermal energy in the U.S.

## 2. CASE STUDIES

LBNL has been working with multiple operators to deploy seismic monitoring systems at geothermal fields (Figure 1). Sensor specifications and duration of monitoring are listed in Table 1. In the following subsections, we show the details of the network at several geothermal sites.
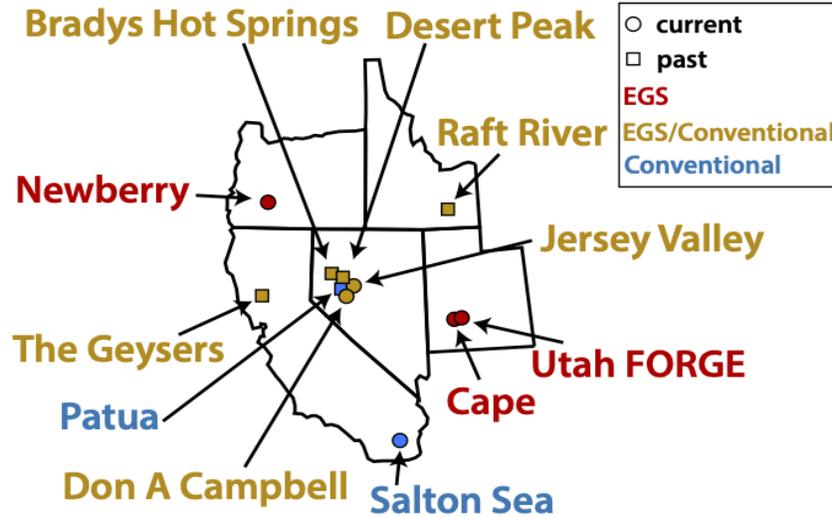


**Figure 1: Map of geothermal fields, where LBNL has deployed seismic monitoring systems discussed in the main text. The red, yellow, and blue marks indicate EGS, a combination of EGS and conventional, and conventional geothermal sites, respectively. The circle and square symbols are current and past seismic monitoring.**

| Site | Seismic monitoring term | Seismic stations | EGS Injection | Key publications |
|------|------------------------|------------------|---------------|------------------|
| The Geysers | 1974-present | (34) 3C, 4.5 Hz 500 s/sec<br>(5) 3C, 2.0 Hz, 500 s/sec<br>(100) 3C, 4.5 Hz<br>(1) strong motion | 2011 | Garcia et al. (2016)<br>Rutqvist et al. (2016) |
| Brady Hot Springs | 2010-2019 | (8) 3C, 8.0 Hz, 500 s/sec (6 borehole)<br>(6) 3C, 2.0 Hz | 2011, 2013 | Akerley et al. (2021) |
| Raft River | 2010-2022 | (9) 3C, 4.5 Hz, 500 s/sec (3 borehole)<br>(15) 3C, 4.5 Hz | 2011 | Bradford et al. (2017) |
| Desert Peak | 2008-2016 | (10) 3C, 4.5Hz, 500 s/sec (4 borehole)<br>(6) 3C, 2.0 Hz | 2010-11, 2013 | Akerley et al. (2021)<br>Banato et al. (2016) |
| Newberry | 2010-present | (8) 3C, 4.5 Hz, 500 s/sec (7 borehole)<br>(1) strong motion<br>(~20) 3C, 5.0 Hz, 1000 s/sec | 2012, 2014, 2024 | Cladouhos et al. (2016)<br>Templeton et al. (2020)<br>Sonnenthal et al. (2015) |
| Salton Sea | 2022-2023 | Darkfiber DAS<br>(80) 3C, 5.0 Hz | | Ajo-Franklin et al. (2022) |
| Patua | 2012-2013<br>2021-2023 | (6) 3C, 15 Hz, borehole (18 stations in 2012-2013)<br>(6) 3C, 2.0 Hz, surface | | Nakata et al. (2023) |
| Cape Modern & Utah FORGE | 2023-present | (6) 3C, 4.5 Hz, borehole<br>(500-1000) 3C, 5.0 Hz, surface | 2019, 2022, 2024- | Nakata et al. (2024)<br>Nakata et al. (2025) |
| Don A Campbell | 2021-present | (6) 3C, 15 Hz highTemp, borehole; (3) 3C optical accelerometer, borehole | FY26 | |
| Jersey Valley | 2022-present | (8) 3C, Optical accelerometer, borehole | FY26 | |

**Table 1. Seismic monitoring specification for each site with injection activities, if present.**

## 2.1. Cape Modern and Utah FORGE

Six seismic monitoring stations and 500-1000 temporal nodal stations were installed to monitor seismic activities at the Cape Modern and Utah FORGE site aimed at complementing the extensive, preexisting monitoring network of the University of Utah Seismograph Stations, in collaboration with the Utah FORGE site (Figure 2). Five of the sensors are installed in shallow (~40 m deep) boreholes, and the other is installed in a ~1 m deep posthole at a hard rock site. All six sensors are 3-component, low-noise optical accelerometers manufactured by Silicon Audio and ASIR Seismic (who package the downhole sondes). They have a nominal sensitivity of 60 V/g, a dynamic range of 172 dB, and a passband from 0.005 to 1500 Hz (per manufacturer specifications; Hopp et al., 2022). Data from these stations are streamed to the EarthScope DMC in real time over the cell network and are archived under the network code 6K. Temporal stations are mostly

SmartSolo IGU 16HR 3C 5Hz and a few of SmartSolo IMU. Example waveforms recorded by the nodes show clear arrivals with a reasonable moveout (Figure 3).
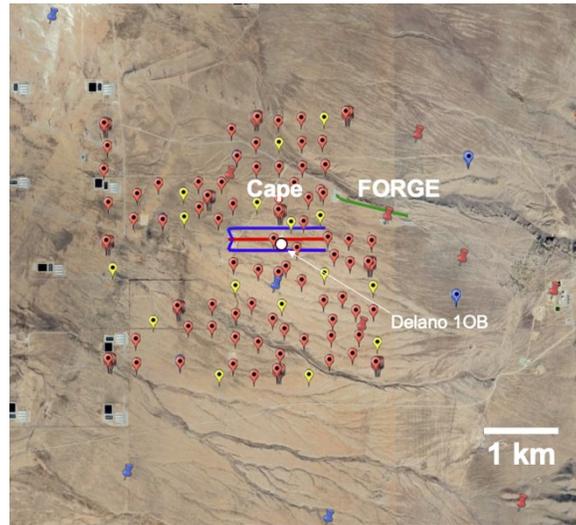


**Figure 2: The site map of the Cape Modern and Utah FORGE geothermal fields at Milford, Utah. The push pins are background seismometers, and the circular pins indicate the location of surface nodal stations. The white circle is the location of the vertical well, which is instrumented by DAS.**
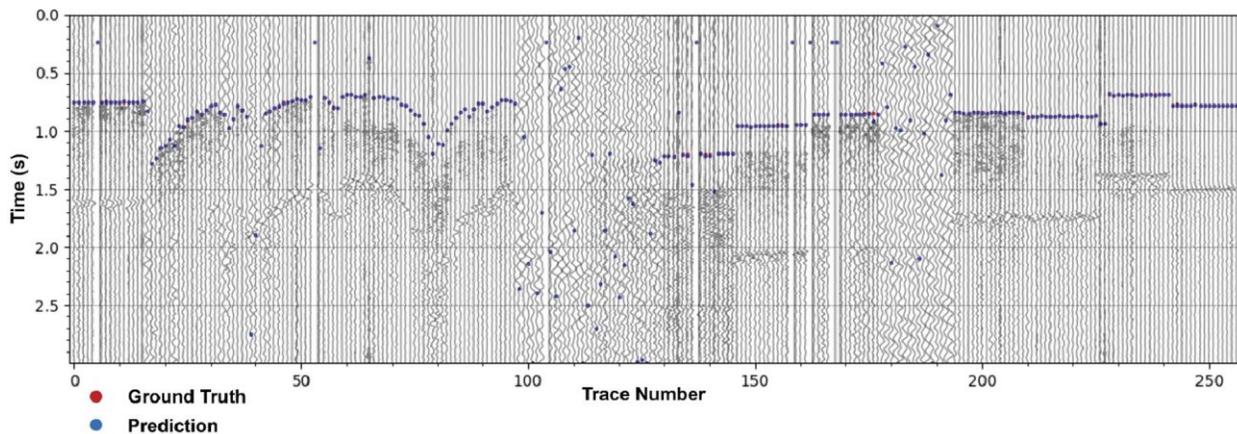


**Figure 3: Example waveforms of an M0.45 earthquake at the Cape Modern site recorded by the surface nodal sensors with P-arrival picks (blue dots) and synthetic picks based on our velocity model (red dots – mostly overlapped with the blue dots). The trace numbers are based on the deployment history.**

### 2.2. Newberry

The seismic monitoring system currently deployed at the Mazama Newberry EGS site closely resembles the configuration used during AltaRock's earlier projects in 2012 and 2014 (Sonnenthal et al., 2015; Cladouhos et al., 2016). It includes eight sensors placed in boreholes reaching depths of up to 300 meters (Figure 4). Of these, six (NN07, NN09, NN17, NN19, NN21, and NN24) are the original 2 Hz geophones since 2012, while the remaining two (NN18 and NN32) are broadband accelerometers added in 2023. The collected data is streamed nearly in real time to the EarthScope Data Management Center (DMC), where it is publicly accessible.

Additional seismic coverage is provided by nearby stations operated by the University of Washington's Pacific Northwest Seismic Network (PNSN) and the USGS Cascades Volcano Observatory (CVO).

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All data from these stations is processed in real time using LBNL's detection and analysis system, which identifies, locates, and estimates magnitudes of seismic events related to the ongoing injection activities at the Newberry site.
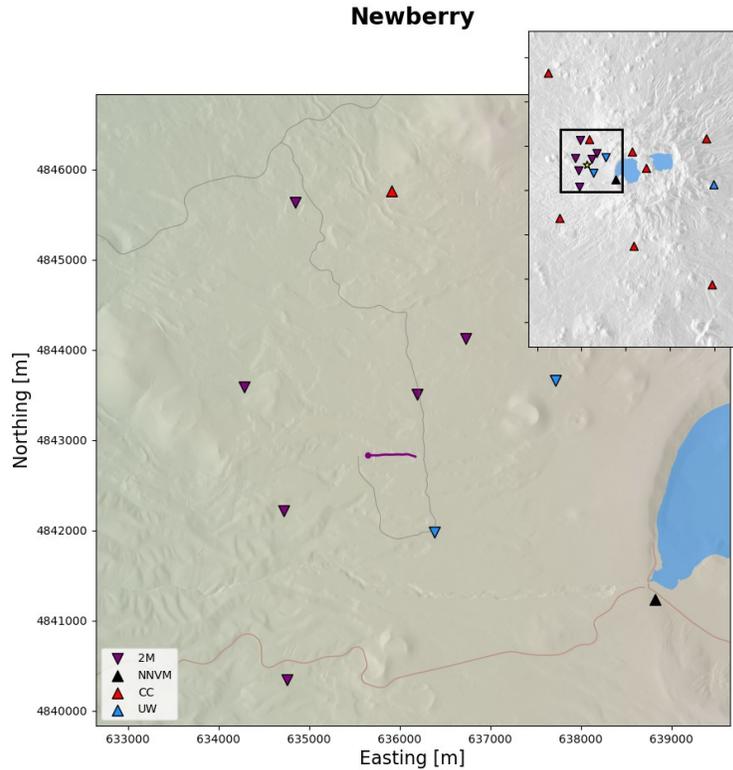
**Newberry**



Figure 4. Map of the seismic monitoring network at the Mazama EGS site. The injection well (55-29) is shown as a purple stem with a circle at the wellhead. Purple inverted triangles indicate the locations of stations with telemetry is hosted by LBNL, blue triangles indicate telemetry hosted by PNSN, and red triangles are operated by USGS (CVO). A strong-motion sensor is installed in a forest service warehouse to the southeast (black triangle).

## 2.3. Patua Geothermal site

Between July 2012 and late 2013, an array of 18 borehole 15-Hz geophones operated at Patua. While most equipment was removed afterward, many sensors remained grouted or locked in place. In June 2021, LBNL began reinstalling recorders and testing these geophones. A 2-Hz surface geophone was also added at each site to assess sediment attenuation. From 2021-2023, data were recorded from six of the original borehole sensors (Figure 5).

The Patua network aimed to detect and locate as many earthquakes as possible to reduce seismic risk and map active structures that are essential to reservoir flow modeling. With all 18 borehole sensors, the network achieved a completeness magnitude of ~0.0, capturing events linked to fractures as small as 5–10 meters (Nakata et al., 2023).
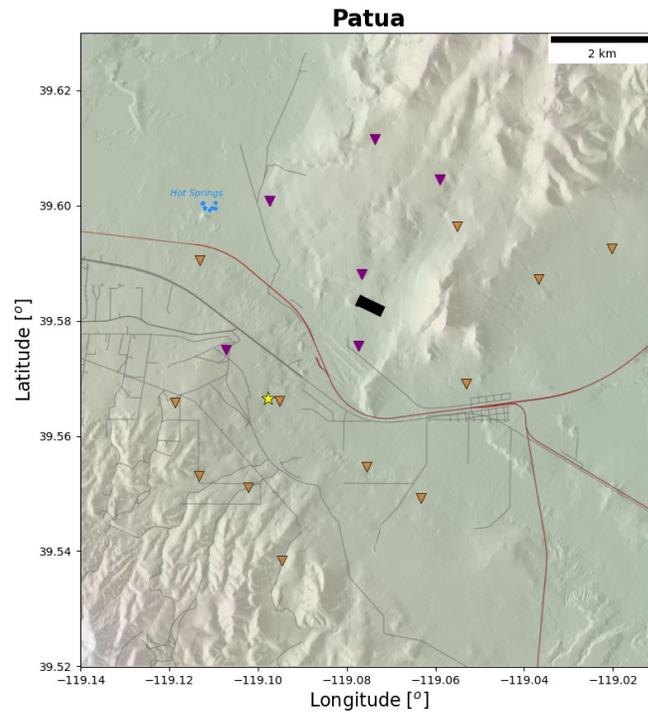
4

**Figure 5: Overview of the Patua geothermal field indicating the locations of previous seismic network sites (brown triangles) and sites that have been reoccupied at some point in the last two years (purple triangles). The location of the proposed stimulation well is shown as a yellow star and the power plant is shown as a black rectangle.**

### 2.4 Don A. Campbell

As part of the Amplify EGS project (Robertson et al., 2022), LBNL has installed nine borehole seismic stations to monitor a forthcoming stimulation planned for the Don A. Campbell geothermal field in Mineral County, Nevada. The sensors were installed between August and December 2023 at depths between 60 and 95 meters and are either 15 Hz high-temperature geophones or low-noise broadband optical accelerometers. Data are recorded at 1 kHz and sent in real-time to both LBNL and the EarthScope DMC where they are archived under the network code 1Q.
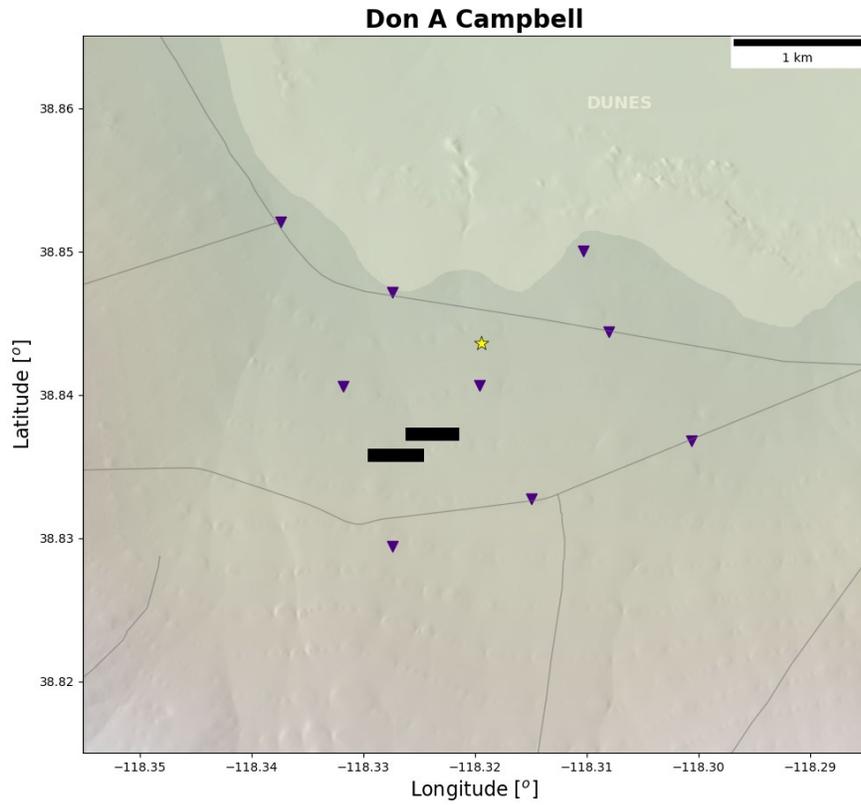
**Figure 6: Overview of the Don A. Campbell geothermal field indicating the locations of seismic network sites (purple inverted triangles). The location of the proposed stimulation well is shown as a yellow star, and the power plant is shown as two black rectangles.**

### 2.5 Jersey Valley

Located in Pershing County, NV, the Jersey Valley geothermal field is also a part of the Amplify EGS project. Between February and May 2025, LBNL installed eight broadband, low-noise optical accelerometers in boreholes at depths between 50 and 200 meters. As with the Don A. Campbell network, these data are recorded at 1 kHz and are archived at LBNL and also at the Earthscope DMC. The network code for the Jersey Valley network is XH.
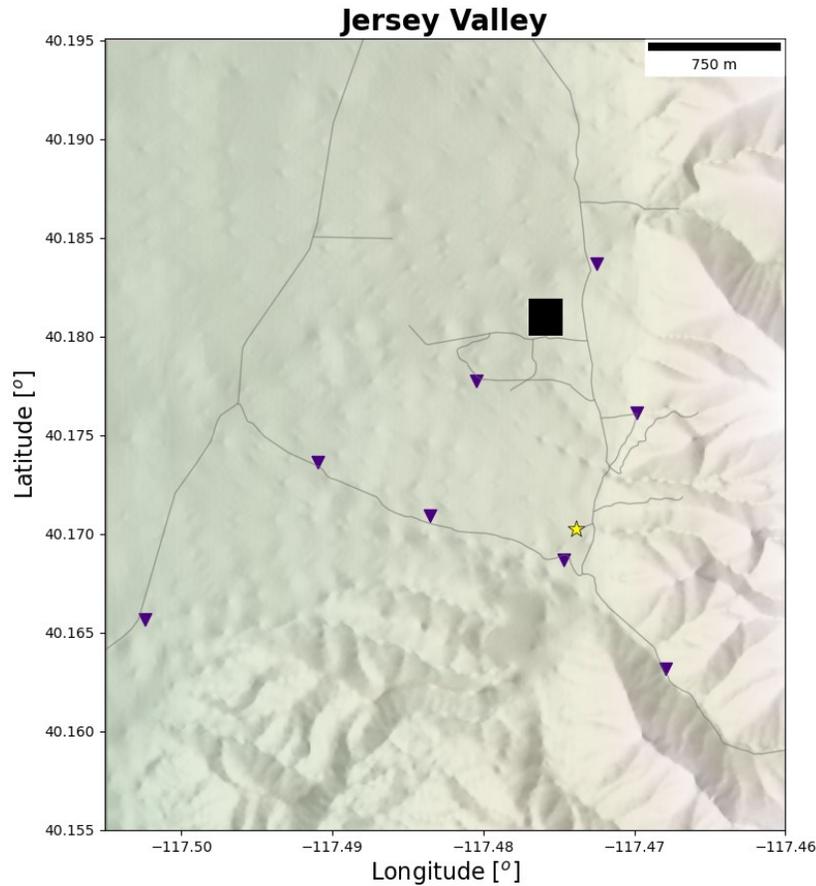
**Figure 7: Overview of the Jersey Valley geothermal field indicating the locations of seismic network sites (purple inverted triangles). The location of the proposed stimulation well is shown as a yellow star, and the power plant is shown as a black rectangle.**

### 2.6 The Geysers

The Berkeley Geysers (BG) network has been in existence since 1989, with seismic monitoring at The Geysers dating back to the 60's. A total of 40 stations have been installed since 2003 and are currently in operation. This seismic network provides the magnitude completeness of 0.8 across the entire Geysers reservoir. The network at the Geyers is currently managed by Calpine, and the data are available through the Northern California Earthquake Data Center (NCEDC) with a network code BG.

### 2.7 Desert Peak

In 2010, a 14-sensor network was jointly installed by LBNL and USGS to monitor the EGS activities at the Desert Peak geothermal field in Churchill County, NV. In 2011, the network was expanded with an additional four boreholes at 300 ft.  The network was in operation from 2008 until 2016, spanning the injection activities that lasted from September 2010 until March 2013 (Ackerly et al., 2021; Chabora et al., 2012).

### 2.8 Brady's Hot Springs

Following the injections at Desert Peak, LBNL installed six 300 ft-deep 3C borehole sensors and three surface sensors to monitor EGS injection activities at Bradys Geothermal Field, approximately 5 miles northwest of Desert Peak in Churchill County, NV. The network recorded from 2010-2019 (some sensors), with the main focus being the April-October 2013 injection activities at the field (Akerley et al., 2021).

**2.9 Raft River**

The Raft River seismic network was installed beginning in August 2010 and removed in November 2022. For most of its life, it comprised four 100-ft deep borehole geophones and four surface geophones and was installed to monitor the EGS demonstration project that included multiple stimulations from February 2012 through the end of 2013 (Bradford et al., 2017; Li et al., 2017).

**3. AUTOMATIC PROCESSING SYSTEM**

Because many of our seismometers have been used as a regional seismic monitoring network, regional geological surveys process the recorded data, and the data product (i.e., earthquake catalog) is published through USGS. It is still meaningful to develop our own processing system to focus on seismicity at geothermal sites, lowering the magnitude of completeness, and supporting scientific research.

Recently, LBNL has set up an automatic processing system of seismicity using the background seismic network using *seiscomp* (Helmholtz-Centre Postdom, 2008). We then refine the automatically processed earthquake catalog using other datasets. The seismic data processing pipeline for the LBNL seiscomp server comprises the following parts:

1.      Data telemetry over the cellular network using the RTP and seedlink protocols

2.      Initial detection is conducted using a short-term average/long-term average (STA/LTA) detection algorithm. The detection statistic is calculated on vertical component data bandpass filtered between 3 and 30 Hz with a short-term window of 0.1 seconds and a long-term window of 5 seconds. When the short-term/long-term ratio exceeds 3, a detection is triggered. The detection is turned off once the ratio falls below 1.5. Parameters would be adjusted at each site.

3.      Once a detection is triggered, seiscomp launches both a P and S-phase post-picking algorithm to refine the arrival times. Both of these algorithms are based on the Akaike Information Criterion (AIC; Akaike, 1973).

4.      All phase picks made by steps 2 and 3 are fed to a phase association algorithm. The phase association is a cluster search based on the DBSCAN algorithm (Ester et al., 1996), whereby P-picks are continually clustered and associated. The clustering metric is the vector sum of the time difference between any pair of picks and the travel time between the stations corresponding to these picks (assuming some average crustal velocity). Once a cluster of P-picks has been formed, additional picks can be associated with this origin from later picks and other origins.

5.      Each final origin created in step 4 is then relocated using a linearized location algorithm with a 1D velocity model tailored to the region in which the picks were made.

6.      If an initial location falls within a set of predefined regions (within 25 km of an injection well, for example), the origin is then relocated using the NonLinLoc software package with a 3D velocity model (Lomax et al., 2009).

7.      Two types of magnitudes are typically estimated: local magnitude (Ml) and duration magnitude (Md). For each pick made, an Ml and Md station magnitude is estimated (Ml being amplitude-based and Md being based on the duration of the event waveform). The network magnitude for each type is computed as the average of all station magnitudes, ignoring outliers beyond the upper and lower 12.5 percentile.

**4. LESSONS LEARNED FROM SEISMIC MONITORING OF EGS AND CONVENTIONAL GEOTHERMAL FIELDS**

LBNL has been actively monitoring and studying microearthquake (MEQ) activity in geothermal fields since the 1970s, starting with The Geysers and expanding to other regions, including Nevada (Majer 1978; Majer and McEvilly, 1980). Over time, LBNL contributed to international efforts, leading to the development of the "Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems" (Majer et al., 2009, 2012) and the subsequent "Best Practices" documents (Majer et al., 2012, 2016, 2025). These guidelines, although not state-of-the-science, provide practical strategies grounded in proven methods for hazard mitigation and reservoir management. They are updated as new technologies and insights emerge and are especially valuable for public engagement and regulatory compliance (see Steps 2, 4, and 7 of the Best Practices).

LBNL's work generally serves two purposes: (1) collecting and analyzing MEQ data to assess and mitigate induced seismicity risks while promoting public acceptance, and (2) leveraging MEQ data to optimize reservoir performance using advanced seismic instrumentation.

**4.1 Hazard and Risk Mitigation**

Experience has shown that proactive outreach is critical—engaging stakeholders before, during, and after drilling can greatly influence project success. Transparent communication, including a balanced explanation of risks and benefits, can convert skeptical stakeholders into supporters. Clear descriptions of mitigation strategies—ranging from engineered approaches (e.g., injection rate adjustments using Traffic Light Protocols) to adaptive frameworks (e.g., Adaptive Traffic Light Protocols or ATLP; Zhou et al., 2024)—are key to building trust. Indirect mitigation, such as managing liability or working with regulators, is equally important. The acceptable level of risk will vary by project.

**4.2 Seismic Data Collection for Reservoir Management**

Following the stimulation at Desert Peak, it was determined that the magnitude of completeness of the catalog was too high to capture the smaller, more numerous events needed to illuminate reservoir structure in the required detail (Ackerly et al., 2021). Since 2011, LBNL has increasingly deployed seismic sensors in boreholes to reduce noise and detect smaller magnitude events, a necessity for illuminating

reservoir structures at high resolution. Achieving a magnitude of completeness below M0.0 is often critical for reservoir management. In parallel, dense arrays of surface nodal seismometers and geophone strings wired in series have improved detection sensitivity and spatial resolution while reducing the deployment cost with drilling. These configurations often rival borehole quality, especially when subsets of the nodes are streamed in real time to enhance monitoring density.

Today, data streaming is no longer constrained by telemetry bandwidth; even 3G networks can stream 1 kHz three-component data. When cellular connectivity is unreliable, satellite telemetry offers a robust, cost-effective alternative—as demonstrated at Jersey Valley, where a satellite backhaul replaced an inadequate cell network.

An effective MEQ monitoring system should provide:

- Accurate event locations (x, y, z, t ± 0.5 km)
- Broad magnitude coverage (from M–2.0 to M+4.5)
- Focal mechanisms (even without full moment tensors)
- Seismicity rates (e.g., Gutenberg-Richter statistics)
- Real-time data access for all stakeholders

For engineering applications, real-time, high-resolution seismic data can validate fluid injection strategies and guide operations. Monitoring systems should ideally digitize at ≥500 Hz with 24-bit resolution and 120 dB dynamic range. A good P- and S-wave velocity model is essential for accurate location and interpretation.

### 4.3 Network Design Considerations

Designing seismic arrays involves balancing cost, sensitivity, and coverage. Borehole sensors offer high sensitivity but limited spatial coverage; surface stations offer broader coverage but higher noise. Advances in fiber-optic sensing and downhole geophones enable deployment in higher-temperature zones (>225°C), though fully capable three-component broadband sensors (>0.01–1000 Hz, 150 dB dynamic range) remain a pressing need for long-term deployment in 3" boreholes. These sensors would enable the detection of subtle failure mechanisms (Mode I, II, III) near stimulation zones.

Land access and permitting also influence station placement—surface stations are usually easy to permit, but borehole installations on public lands (e.g., BLM, USFS) may take months. Real-time telemetry, power supply, and terrain accessibility are other key constraints that must be considered in early planning stages.

### 4.4 Sensor Calibration and Verification

Prior to operation, calibrating the seismic network is essential. This includes checking sensor polarity and confirming timing consistency across stations using known sources (e.g., explosions), side-by-side comparisons, or large regional events with well-constrained ground motion. Such procedures are critical for accurate focal mechanism and moment tensor inversion.

### 5. Conclusions

Through LBNL's multi-site monitoring deployments and real-time data processing systems, we have gained critical insights into induced seismicity at geothermal fields and developed scalable methods for seismic data acquisition and analysis. Our experience underscores the importance of long-term, high-resolution monitoring networks tailored to local geologies, combined with automated detection pipelines. These systems not only reduce the magnitude of completeness but also enhance seismic risk mitigation and support broader research objectives through public data access.

Accurate and timely seismic data collection is foundational for both managing induced seismicity risks and improving geothermal reservoir performance. As geothermal deployment scales up and targets deeper, hotter, and more complex formations, robust MEQ monitoring will play a central role in ensuring safe, effective, and publicly accepted enhanced geothermal system (EGS) projects.

### ACKNOWLEDGEMENT

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