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Real-time Microseismic Processing for Induced Seismicity Hazard Detection

E. M. Matzel

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Real-time Microseismic Processing for Induced Seismicity Hazard Detection

Eric Matzel (14-ERD-051)

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Abstract

Induced seismicity is inherently associated with underground fluid injections. If fluids are injected in proximity to a pre-existing fault or fracture system, the resulting elevated pressures can trigger dynamic earthquake slip, which could both damage surface structures and create new migration pathways.

The goal of this research is to develop a fundamentally better approach to geological site characterization and early hazard detection. We combine innovative techniques for analyzing microseismic data with a physics-based inversion model to forecast microseismic cloud evolution. The key challenge is that faults at risk of slipping are often too small to detect during the site characterization phase. Our objective is to devise fast-running methodologies that will allow field operators to respond quickly to changing subsurface conditions.

Background and Research Objectives

A natural response to fluid injection is the creation of microseismicity. Often thousands of microquakes are associated with an injection well. These microquakes are not of concern, as they are far too small to be felt at the surface. However, they effectively illuminate the subsurface, allowing us to monitor plume growth and identify previously hidden faults. Precise seismic measurements on these microquakes is key.

Unlike natural seismicity, fluid-induced seismicity is strongly time- and space-dependent, driven by injection rate and pressure. To correctly address the induced seismic hazard, it is therefore necessary to introduce a strong hydromechanical underpinning. Current state-of-the-art methods for dealing with induced seismicity have several key deficiencies which motivate the proposed work. In particular, current efforts almost exclusively use ad hoc or empirical approaches that are based on weak hydromechanical foundations. Also, these methods typically rely a few simple measurements such as event location and magnitude, and ignore source mechanism information hidden in the data.

Our approach is centered around several geophysical techniques. Each of these exploits different information embedded in the seismic data, as well as our understanding of the hydromechanical behavior of reservoir systems. Several of these algorithms have been previously developed and applied for global scale seismic monitoring, but have had limited microseismic application.

This project is organized around pre-existing data sets from field operations, in particular the Newberry and Salton Sea geothermal fields, which are well instrumented and have significant injection-related microseismicity. Field data provide an opportunity for extensive validation exercises, and allow us to test our techniques in noisy and data-limited environments. We also generate synthetic case studies using high performance computing resources to gain a complete understanding of the underlying physics.

Scientific Approach and Accomplishments

The purpose of the geophysical analysis is to monitor the microseismicity associated with fluid injection. We want a sharp image of the subsurface in order to identify any faults or zones of weakness. We also want to identify changes in that image as injection proceeds. Since the shape of the microseismic cloud is driven by the evolution of the pressure front, tracking the pressure front involves locating the microquakes precisely and increasing the completeness of the catalog by detecting very small events. The techniques we focus on are summarized below:

- *Ambient Noise Correlation* (ANC) is a form of seismic interferometry, in which long periods of background noise recorded by the array are used to estimate the 3D velocity and attenuation structure of the earth. The velocity model is used in many downstream analyses, and therefore a high-quality 3D model is essential to achieving high accuracy and low uncertainty.
- *Matched Field Processing* (MFP) is a seismic event detection algorithm, used to identify discrete microseismic events in the continuous waveform data. MFP is superior to many standard algorithms—such as Short-Term Average / Long-Term Average detection algorithms—at identifying small magnitude events near the noise-floor of the data. It therefore provides a more complete picture of the seismicity occurring in the field.
- *Bayesian Location* (BayesLoc) is an event relocation and uncertainty estimation tool that uses Bayesian inference to rigorously account for potential sources of uncertainty in the data. The analysis provides the most likely location of microseismic events, and confidence volumes quantifying the intrinsic location uncertainty. As absolute location uncertainties can often be very large (potentially hundreds to thousands of meters) a good understanding of these confidence volumes is essential to making informed decisions about fault structures that may be observed.
- *Virtual Seismometer Method* (VSM) is another form of seismic interferometry that employs cross-correlations between pairs of microseismic events. It is very sensitive to the earth structure between event pairs and their focal mechanisms. Using the VSM analysis, we can cluster events that exhibit similar focal mechanisms. This clustering is essential to distinguishing larger, coherent fault structures from diffuse seismic sources (such as fractured zones) that create lower hazard.
- *Empirical Forecasting*. The Empirical Forecasting algorithms use a statistical model to connect injection rate with observed seismic event frequency and magnitude distribution. This model has relatively few free parameters, which are continuously recalibrated to observed data as injection proceeds. The calibrated

model may then be used to forecast future event frequency within some forecast window. This tool provides a way to estimate the current level of seismic hazard, and how it may evolve based on different injection scenarios.

Each of these techniques has particular strengths and when used in combination, can greatly increase the resolution of the subsurface. The net result of these analyses is detailed information about field behavior for the operator: characterization data regarding earth structure, reactivated faults, and ongoing seismic hazard, warning if pressure and stress perturbations occur in unexpected locations, and an understanding of the intrinsic sensitivity of the monitoring array and any uncertainties associated with the results. If the results raise a red-flag, this information can be combined with other monitoring data and analyses to make well-informed but rapid decisions about how best to deal with seismic hazards.

A key objective of this research is to develop algorithms that can be run quickly, in near real-time, to allow operators to respond quickly to changing field conditions. With the exception of ANC, all of the techniques described above can be run on a standard computer within a few hours of accessing data. The advantage of ANC is that the calculations can be done inexpensively, before operations even begin.

Ambient Noise Correlation resolves the large-scale structure from the surface through the seismically active zone

A major advantage of the ANC technique is that it strips away the dependence on earthquakes or artificial sources for seismic imaging. Problems of source location and velocity heterogeneities outside the region of interest are no longer present, only the structure between the seismometers contributes to the signal. In particular, it allows high resolution imagery beneath dense seismic networks even in areas of low seismicity (Campillo and Paul, 2003).

Using ANC, we can obtain detailed images of the 3D structure surrounding an injection site. These images are precise enough that we can identify the source of the scattered energy seen in the data. An example of this is shown in Figure 1. Typically, this scattering would be treated as noise and discarded, because it isn't captured by simpler models. With precise 3D models we can use subtle details in the recorded seismograms to locate the seismicity more precisely and to identify the style of faulting. We can also predict where future microseismicity will occur, as it generally falls near the most rapid changes in the velocity gradient.

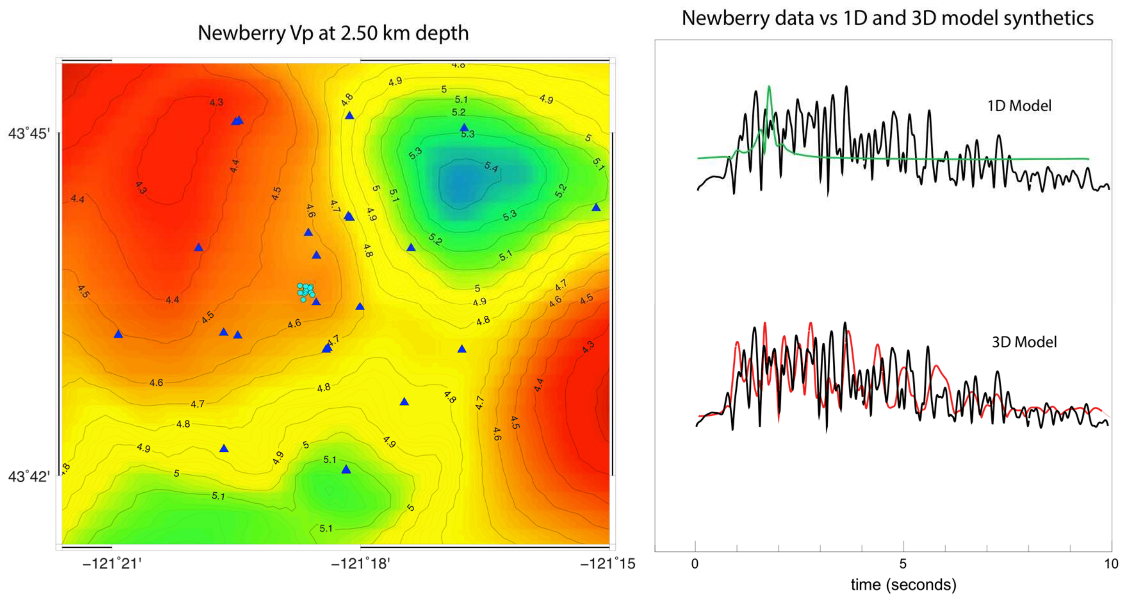

Figure 1 (left) Horizontal slice at 2.5 km depth through the 3D Vp model developed using ANC at the Newberry site. Dark blue triangles are network stations. Light blue circles are observed microseismic events. (right) Record of the 12/01/2012 microquake recorded by Newberry network station NB19 (black) compared with the synthetic seismograms from the reference 1D (green) and ANC-derived 3D (red) models. The 3D model is much better at reproducing the scattering energy seen in the waveform coda.

Extending the completeness of the catalog using Matched Field Processing

MFP is an adaptation of a signal processing technique originally developed to locate continuous underwater acoustic sources (Baggeroer et al., 1993; Bucker, 1976). We calculate the wavefield structure across an array by estimating it directly from previously observed earthquakes which contain contributions from direct and scattered seismic energy. MFP detects small microseismic events that are often buried in the noise, extending the completeness of the catalog (Figure 2). These small events are valuable because they fill in details of the evolving pressure field. Regions that appear quiet may actually be quite active and small events are often precursors to larger ones.

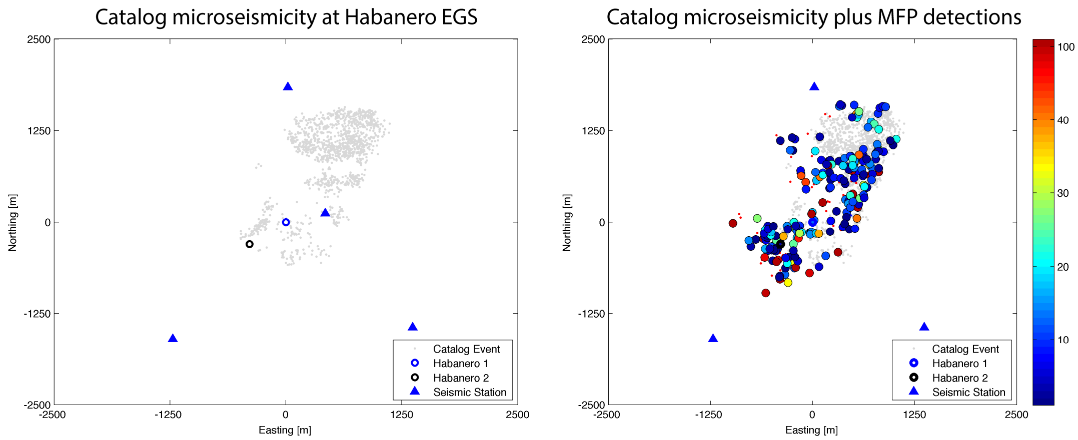

Figure 2 Microseismicity during the 2005 Habanero EGS Simulation in the Cooper Basin of South Australia. (left) 1288 microquakes were originally identified and located during the first week of stimulation. (right) MFP identified 994 additional events buried in the noise.

Bayesian Location

We simultaneously locate multiple micro-earthquakes following the Bayesian methodology of Myers et al. (2007). Bayesloc allows for probabilistic constraints on the arrival-time data, the travel time model, and the location parameters. BayesLoc also provides an estimate of location uncertainty, an essential feature to help distinguish real from phantom faults.

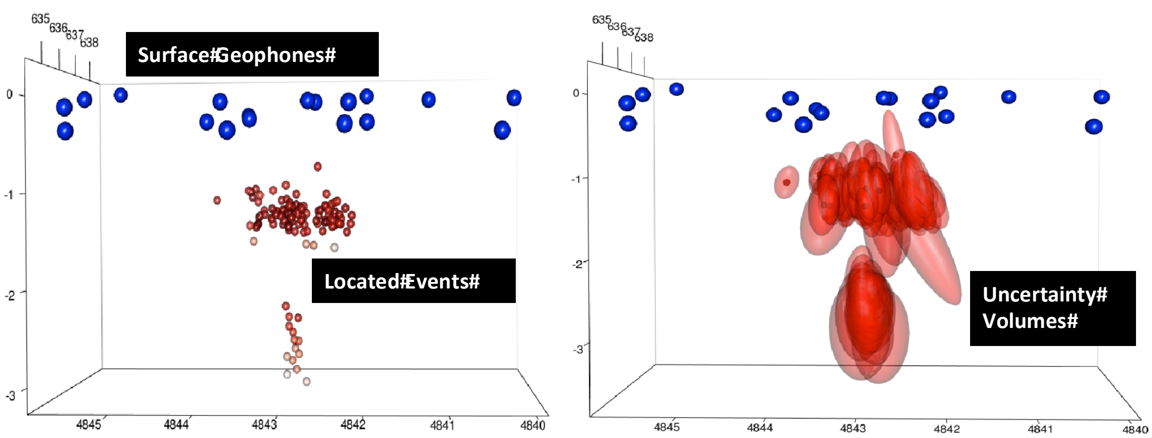

Figure 3 (left) Locations of microseismicity recorded by the Newberry array (network in blue). Darker colors indicate events that are more precisely located. (right) The uncertainty in seismic locations represented as plots of the 95% confidence ellipsoids.

At Newberry, we chose a subset of 199 events with 1441 P picks and 1267 S-wave picks. Figure 3 shows the locations along with their estimated accuracy. Note that the uncertainties in the locations are very large. Vertical errors are significantly larger than the horizontal errors, primarily due to the recording station geometry.

The cause of the relatively large uncertainty of the deeper events is due to small errors in the S-wave picks. Rotating the P- and S-wave energy to better isolate the S-wave particle motion improved picking accuracy and significantly decreased the size of the ellipsoids. Together with the improved earth model from ANC, BayesLoc can be used to improve the precision of event locations.

Virtual Seismometers allow us to focus on the zone of microseismicity:

VSM provides fast, precise, high frequency estimates of the Green's function (GF) between earthquakes (Curtis et al., 2009; Hong & Menke, 2006). It illuminates the subsurface precisely where the pressures are changing. This has the potential to image the evolution of seismicity over time, including changes in the style of faulting as injection proceeds (Matzel et al.,2016). Given sufficient microseismicity, we can calculate detailed evolution of the wavefield. Where ANC obtains the large-scale, 3D structure of the entire site, VSM obtains the fine details in the tectonically active zone. An example of the technique at the Newberry geothermal field is shown in Figure 4.

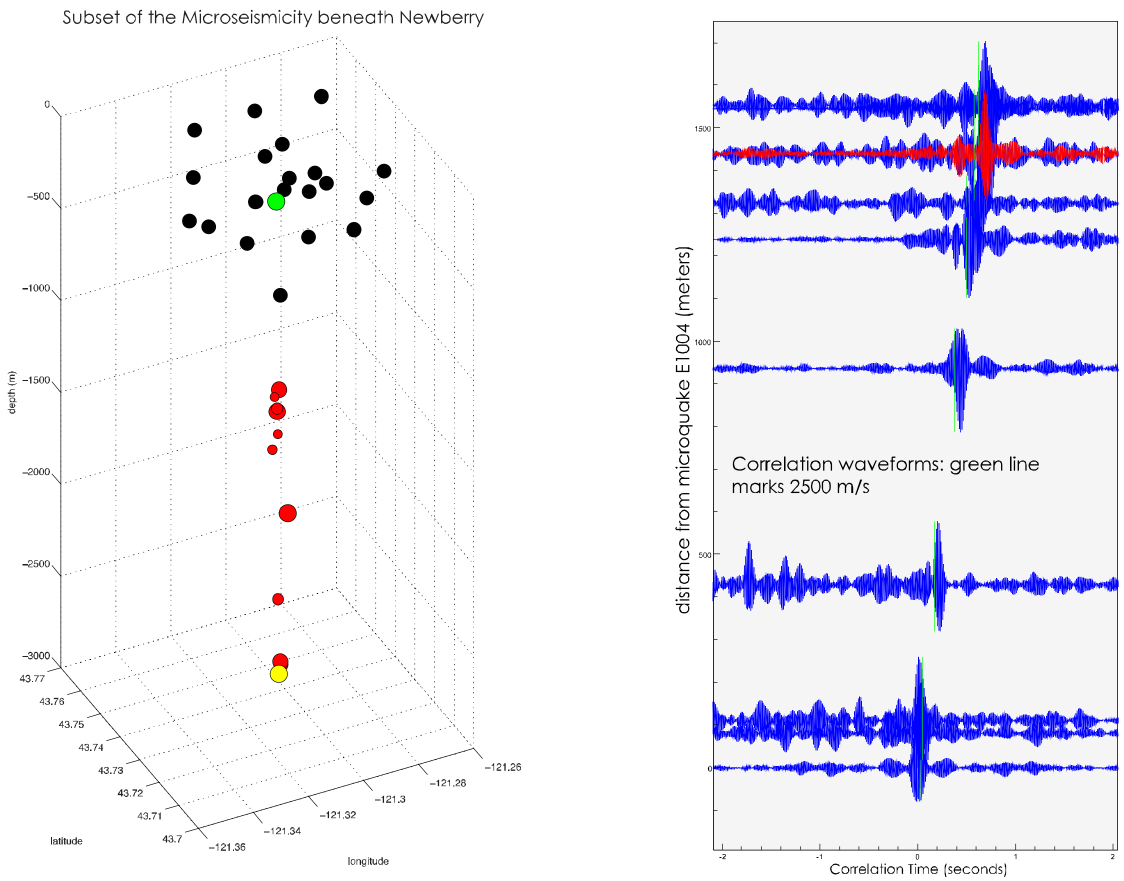

Figure 4 (left) view of the network at Newberry (black circles) and a subset of the microseismicity beneath it (red). The yellow circle denotes a microquake which is being treated as the virtual seismometer recording all the others. The central element of the network (green) was used in the VSM calculations shown at right. (right) Profile of the virtual seismograms.

Short-term Seismic Forecasting:

Empirically-based methods for hazard forecasting use an observed seismicity catalog, compiled from microseismic monitoring of the injection, to estimate the ongoing seismic hazard (Bachmann et al., 2011; Mena et al., 2013; Shapiro et al., 2007, 2010). As the project proceeds, the growing catalog of events is used to continuously re-calibrate a model of earthquake frequency-magnitude distribution. These empirical approaches typically use simplified models of the underlying physical processes, leading to a manageable number of free parameters to be fitted to observed data. The calibrated model may then be used to forecast the future seismic hazard within some forecast window (Bachmann et al., 2011; Mena et al., 2013). The quality of this forecast will depend on the fidelity of the chosen empirical model to the true system behavior, and the availability of sufficient seismic observations to properly constrain future seismic behavior.

Our empirical forecasting algorithm uses a simple statistical model with three free-parameters to connect injection rate with observed seismic event frequency. In particular, the model uses observed injection rates and pressures to calibrate a linear superposition model for pressure evolution in the reservoir. This pressure evolution is then correlated with observed seismic event frequency based on observed data. The model is then continuously re-calibrated to observed data as injection proceeds. The current model provides a rough but reasonable forecast of how seismic event count will change when, for example, the injection well is shut-in. This provides an opportunity to understand how seismic hazard may evolve under various injection-management scenarios.

Impact on Mission

Induced seismicity is an inherent issue associated with energy technologies of particular interest to LLNL: geologic carbon sequestration, enhanced geothermal systems, and shale gas development. A strategy for assessing and mitigating seismic risk needs to be developed if large-scale fluid injection operations are to continue responsibly. Here, we have developed a system of techniques that are fast-enough that they can be applied in real-time and synchronized with data acquisition.

Conclusion

Geologic carbon sequestration, enhanced geothermal systems, and disposal of waste hydraulic fracturing fluid from shale gas development all involve injecting large volumes of fluid into the subsurface. If these fluids are injected near a pre-existing fault or fracture system, they could potentially trigger earthquakes of magnitudes that are sufficiently large to cause serious public concern. Microseismicity is closely associated with these technologies and can be used to monitor the evolution of the pressure field. The technologies developed here allow us to get refined measurements of the developing pressure field and make forecasts as operations proceed. The algorithms are fast and efficient and lend themselves to development for field environments.

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