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An Investigation of the Microseismicity at the Newberry EGS Site

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ABSTRACT

We aim to increase the amount of information that can be extracted from continuous seismic data collected in an Enhanced Geothermal System (EGS). To accomplish our objective, we apply a seismic imaging technique that can map seismicity from known discrete microearthquake sources using the empirical Matched Field Processing (MFP) method. We investigate the seismic activity within the DOE Newberry EGS site and identify more and smaller microearthquakes than with the traditional STA/LTA method alone. The original earthquake catalog identified 235 events while the MFP technique identified 164 additional events. For the events with the highest signal-to-noise ratio, we apply a local Bayesian multiple-event seismic location algorithm that estimated the 95% ellipsoids of the posterior mean locations. The results show that the upper and lower seismic swarms are most probably activating two separate areas of the reservoir.

1. INTRODUCTION

Effective Enhanced Geothermal Systems (EGS) require optimal fracture networks for efficient heat transfer between hot rock and fluids. Subsurface microseismic maps are key tools that can be used as an indirect indicator of the subsurface fracture geometry within the reservoir. Traditional earthquake detection techniques, such as STA/LTA algorithms, are often employed to identify microearthquakes in geothermal regions. However, these commonly used detectors may miss events if the seismic signal of an earthquake is small relative to the background noise level or if a microearthquake occurs within the coda of a larger event.

Consequently, we have focused our attention on a set of algorithms that provide improved microearthquake detection, specifically the Matched Field Processing (MFP) method. The empirical MFP approach uses pre-calculated templates to match the spatial structure of continuous seismic data to a selection of known master templates. In this study we create matched field steering vector calibrations using the high quality Newberry borehole seismic data to identify more and smaller events before, during and after the Newberry EGS stimulations.

For the events with the highest signal-to-noise ratios (SNR), we apply MicroBayesLoc, an LLNL Bayesian multiple microseismic event locator, to microseismic event data recorded across a 15-station network of surface and borehole receivers. Seismic event locations are determined by minimizing the difference between the predicted and observed arrival times while accurately characterizing event location uncertainty.

2. IDENTIFICATION OF MORE MICROEARTHQUAKES USING EMPIRICAL MFP

Our MFP technique differs from traditional earthquake detection techniques and is an adaptation of a signal processing technique originally developed to locate continuous underwater acoustic sources [Bucker 1976; Baggeroer *et al*. 1993]. We calculate the wavefield structure across an array by estimating the structure directly from field calibration data, i.e., previously observed seismic events. Then we steer the array explicitly in the frequency domain using the complex phase and amplitude factors obtained from the field data (Harris and Kvaerna, 2010). We refer to this strategy as empirical MFP, in which the master templates created from the seismograms of previously detected micro-earthquakes contain contributions from direct and scattered seismic energy.

Empirical MFP largely eliminates the sensitivity of (correlation) matching operations to source time history variations by processing the observed data stream in a large number of narrow frequency bands. This makes MFP sensitive to the spatial structure of the signal at the observing aperture (controlled by mechanism and propagation), but not the temporal structure (controlled, in part, by source time history). In this way MFP can identify previously undiscovered events even if they bear little resemblance to the master event in the time domain.

2.1 Original Earthquake Catalog

We merge two catalogs to create a combined original earthquake catalog that spans the time period of this study. We combine the official AltaRock Energy Inc. earthquake catalog with the Lawrence Berkeley National Laboratory Newberry (LBNL) EGS online earthquake catalog. Between October 2012 and February 2013, the AltaRock Energy Inc. catalog identified and located 228 microearthquakes. Excluding nearby regional events that were captured by the LBNL catalog, we identified 7 high-frequency local microearthquakes occurring between March 2013 and September 2013 in the LBNL catalog.

2.2 Creation of Master Matching Templates

Master templates are created from master events. They are used to identify new events in the seismic datastream. The master events are selected based on two criteria. First, calibration events cannot be superimposed on other events in the seismic record. Second, waveforms of master events must also have SNR, especially in the lower frequency ranges, on at least four three-component seismic stations. No other selection criteria based on magnitude, mechanism or location is taken into consideration. Using these criteria, we investigate all events in the original catalog to determine their suitability as master templates. We identify 76 events out of the original 235 catalog events that could be employed as master events.

2.2 Results of Application of MFP to the Continuous Seismic Data

The empirical MFP code compared master templates to the continuous seismic data using a 21-sec sliding window that stepped forward at 1-second intervals. Comparisons between master events and new data were performed in the 8 – 12 Hz frequency band for continuous data between September 2012 and September 2013.

The merged original catalog reported 235 events. The MFP earthquake detection code was able to identify 164 additional events. The vast majority of the new events were located in the shallow seismic swarm.

2.3 Comparison Between Seismicity and Injection Data

We plot the number of seismic events per day and compare it to the daily injected volume and the daily average well head pressure. There is a general relationship between the amount of fluids injected and the number of seismic events per day, however the seismicity appears to be sometimes delayed from the peak in the fluid parameters (Figure 1). Although the stimulation began on Day 290, seismicity did not occur with great frequency until approximately 2 weeks later when the daily injected volume and the average well head pressure reached a peak. Although no events were originally recorded during a small air injection occurring near Day 350, several extremely small microearthquakes were identified using the empirical MFP technique (Figure 1).

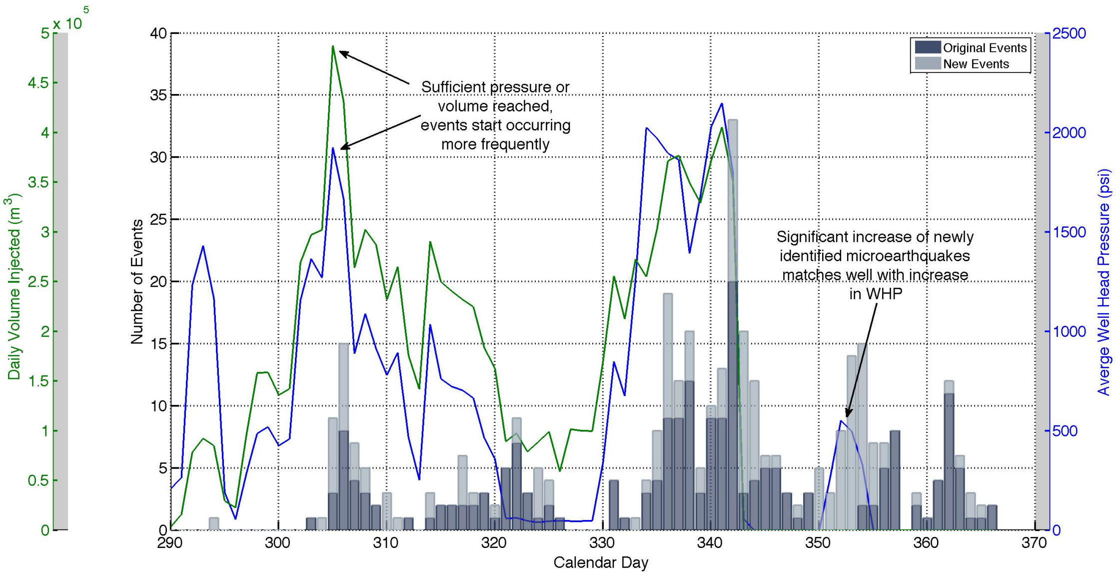

Figure 1: Comparison of the daily number of microseismic events, daily injected volume, and daily average well head pressure. The number of original catalog events are plotted in dark grey and the number of newly detected events are plotted in light grey. The daily injected volume is plotted in green and the daily average well head pressure is plotted in blue.

2.4 Determination of New Event Magnitudes

Duration magnitudes, Md, were determined for the newly identified events. This was accomplished by first determining an average event duration from the vertical components of original catalog events for which there was a P pick and for which there was not another known event within 5 seconds. A linear best fit between the log10 event durations and the original catalog event moment magnitude was calculated. This model was then used to determine duration magnitudes for new events based on their measured event duration.

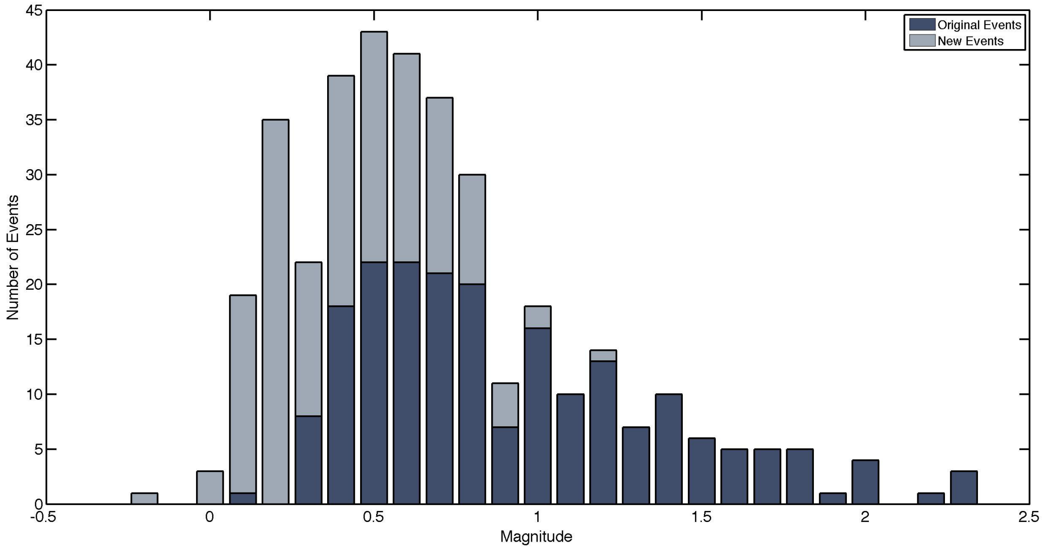

Figure 2: Comparison of the magnitudes of events in the original earthquake catalog, in dark grey, with the magnitude of new events, in light grey. In general, new events tended to be smaller microearthquakes.

3. MICROBAYESLOC EVENT RELOCATION

We locate multiple microseismic events simultaneously following the Bayesian methodology originally implemented in the global-scale Bayesian multiple event seismic locator, BayesLoc (Myers et al., 2007). This Bayesian methodology allows for probabilistic constraints on any combination of the arrival-time data, the travel time model, and the location parameters. Sampling from the resulting Bayesian posterior distribution is accomplished using the Markov Chain Monte Carlo (MCMC) method.

We assume a relatively simple travel-time model for P arrivals based on a linear change in velocity with depth. A 'tuning' parameter for the earth model in the multiple microseismic event location problem is adjusted as part of the Bayesian location problem to yield the best match to the observed data. At the core of the Bayesian locator is a statistical model that links observed data to unobserved parameters through the earth model. The statistical model consists of three main components: (1) a prior probability model for the source parameters in 3D location and time, (2) a statistical model for the correction to the assumed earth model (i.e., the travel-time corrections), and (3) a statistical model for the error in the observed data (e.g., the spread of the arrival-time residuals).

For the Newberry EGS data set, we chose a subset of 199 events with 1441 P picks and 1267 S wave picks. The pick catalog was obtained from AltaRock Energy Inc. Figure 3 shows the posterior marginal densities of the three travel-time parameters. Figure 4 shows the 3D locations of the 199 events along with the receiver locations. The event locations are colored according to their estimated accuracy, represented by the volume of the 95% ellipsoid.

Investigation as to the cause of the relatively large uncertainty of the deeper events showed that relatively small errors in the S-wave picks were the influencing the size of the 95% ellipsoid volume. A test using a small subset of events in which the P- and S-wave energy was rotated to better isolate the S-wave particle motion for improved picking accuracy showed a significant decrease in the size of the ellipsoids. Future work will focus on this area.

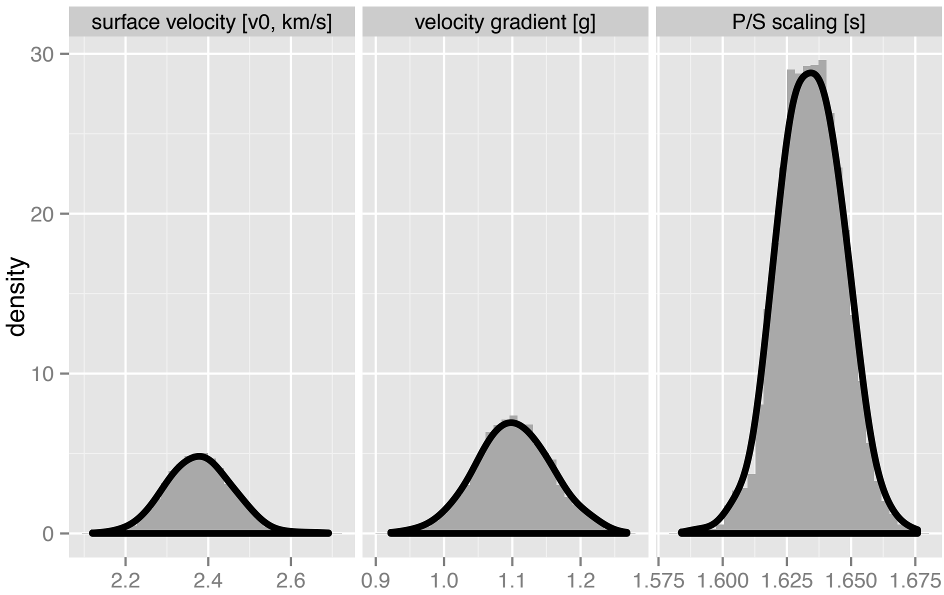

Figure 3: The posterior histogram of the three travel-time model parameters (surface velocity, gradient, and P/S scaling parameter) for the Newberry dataset.

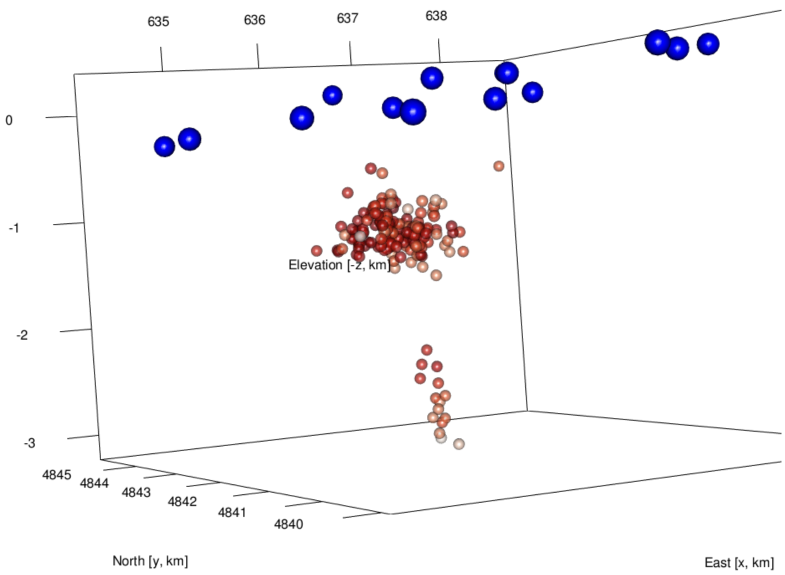

Figure 4: Depth view of event locations colored according to their estimated accuracy, represented by the volume of the 95% ellipsoid. Darker colors are indicative of greater accuracy. The station locations are indicated by the blue circles.

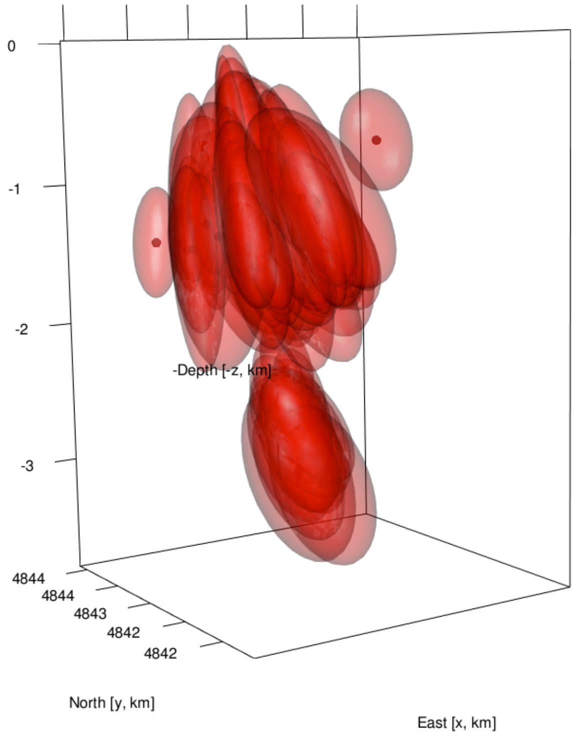

Figure 5: Depth view of event locations posterior mean as the dark red circle and their 95% ellipsoids. Although the vertical errors are significantly larger than the horizontal errors, primarily due to the recording station geometry, the errors are such that the two seismic swarms are most likely occurring in distinct regions of the reservoir.

4. CONCLUSIONS

Using the empirical MFP method, we were able to identify 164 additional events occurring between September 2012 and September 2013 at the Newberry EGS site. There were 235 events in the original merged earthquake catalog during this same time period. These new events were identified using 76 events from the original earthquake catalog as master events in the empirical MFP earthquake detection methodology. We applied the empirical MFP technique to high quality continuous data from 8 borehole sensors in the Newberry microseismic array. These smaller events

The MicroBayesLoc multiple-event locator accurately characterized the uncertainty associated with the seismic data and model. MicroBayesLoc seismic event locations showed that although the location errors were larger in the vertical direction, primarily due to the relatively small aperture of the seismic recording stations, the locations delineated two distinct regions within the reservoir that were activated and illuminated by the upper and lower seismic swarm. Testing indicated that the vertical errors could be decreased by increasing the accuracy of the S-wave picks by rotating the seismograms before phase picking.

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