

## Seismic Interferometry Using the Dense Array at the Brady Geothermal Field

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### ABSTRACT

In March 2016, as part of the Poroelastic Tomography experiment, a large seismic array was deployed over the geothermal field at Brady's Hot Springs in Nevada. This array recorded more than two weeks of continuous data, including several local and regional earthquakes, vibroseis sweeps, and local traffic noise, as well as the ambient seismic wavefield. In this study, we use several methods of seismic interferometry to investigate the site. We focus on two techniques: sweep interferometry uses the energy from the vibroseis sweeps as sources of high frequency energy. Ambient noise correlation uses the energy of the ambient background field. In each case, the data recorded at one seismometer are correlated with the data recorded at another to obtain an estimate of the Green's function between the two. The 238 geophones, concentrated over a 1.5 square-kilometer area, allow us to calculate nearly 30,000 paths, which we use to characterize the site and measure the localized wavefield.

### 1. INTRODUCTION

The Poroelastic Tomography experiment (PoroTomo) was conducted in March 2016 at Brady Hot Springs in Nevada. As described by Feigl et al. (2017), a key goal of the experiment is to understand how fluids travel from shallow aquifers, through faults and fractures, to deep geothermal reservoirs. As part of the effort, seismic, geodetic, and hydraulic technologies are being tested and developed to fully characterize the rock mechanical properties.

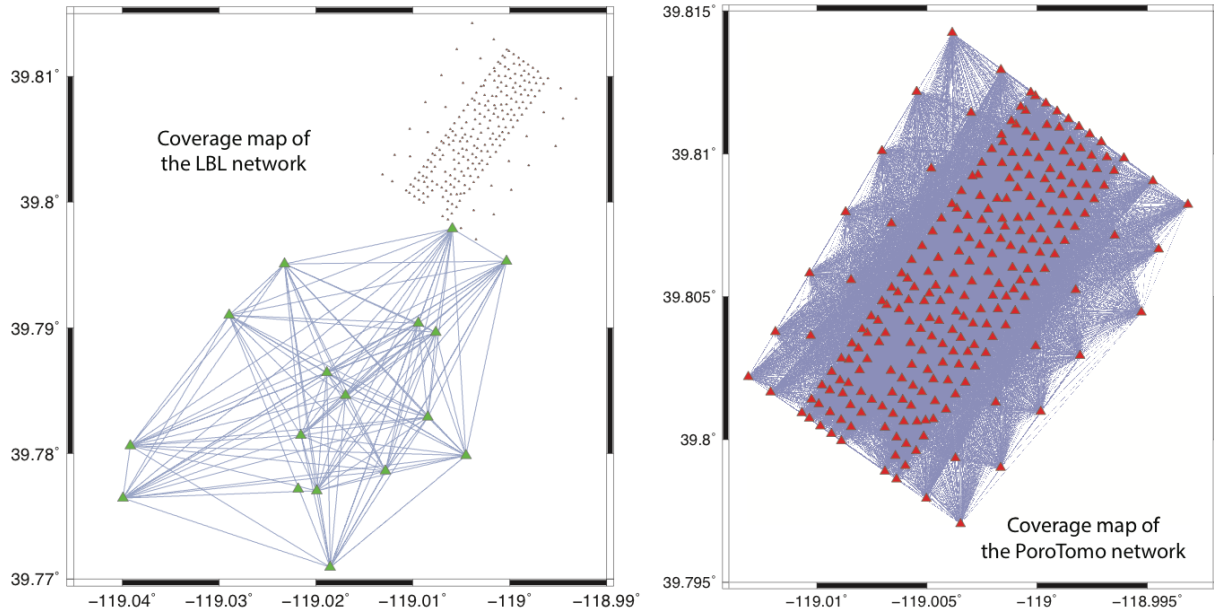
This paper focuses on the application of seismic interferometry to image the velocity heterogeneity at the site.

### 2. INTERFEROMETRY AT BRADY HOT SPRINGS

Seismic interferometry allows us to make precise measurements of the physical properties of the Earth. "Virtual earthquake" methods involve correlating the data recorded at one seismometer with the data recorded at a second to obtain an estimate of the Green's function (GF) between the two. A major advantage of virtual earthquake techniques is that we have perfect knowledge of the location and timing constraints, since they are tied to the instruments. In traditional earthquake seismology, uncertainties in the origin time, location and source mechanism of the events have the effect of blurring the images that can be resolved. Interferometry allows high resolution imagery beneath dense seismic networks even in areas of low seismicity. Velocity heterogeneities outside the region of interest are no longer present and the recovered GF tends to be relatively simple. Only the structure between the instrument-pair contributes to the signal and even subtle differences in the observed waveforms can be interpreted.

One form of seismic interferometry, ambient noise correlation (ANC), is based on the observation that the Earth's background noise includes coherent energy, which can be recovered by observing over long time periods and allowing the incoherent energy to cancel out (Hennino et al., 2001; Weaver and Lobkis, 2001). The cross correlation of ambient noise between a pair of stations results in a waveform that is identical to the seismogram that would result if an impulsive source located at one of the stations was recorded at the other (Campillo and Paul, 2003; Malcolm et al., 2004; Snieder, 2004; Wapenaar 2004). Ambient noise correlation has the advantage that it is entirely passive. The network can be adapted easily to the problem in question, and the resulting GFs are stable enough that 4D variations can be interpreted as changes in subsurface structure. The disadvantages are that we have little control over the frequency content, which is determined by the natural background field, and it typically requires long continuous data records. ANC becomes computationally expensive for high-frequency, large-N data sets. We have applied this approach at Brady, as described by Zeng et al. (2016; 2017).

A second form of seismic interferometry uses the energy of active sources to obtain the GF more quickly. Here, we use a series of vibroseis sweeps that were performed at points surrounding and within the site during the experiment. In this case, we only need short records of the active sweeps required to estimate high frequency GFs. It is computationally much less expensive than ANC, but it tends to be operationally more expensive.

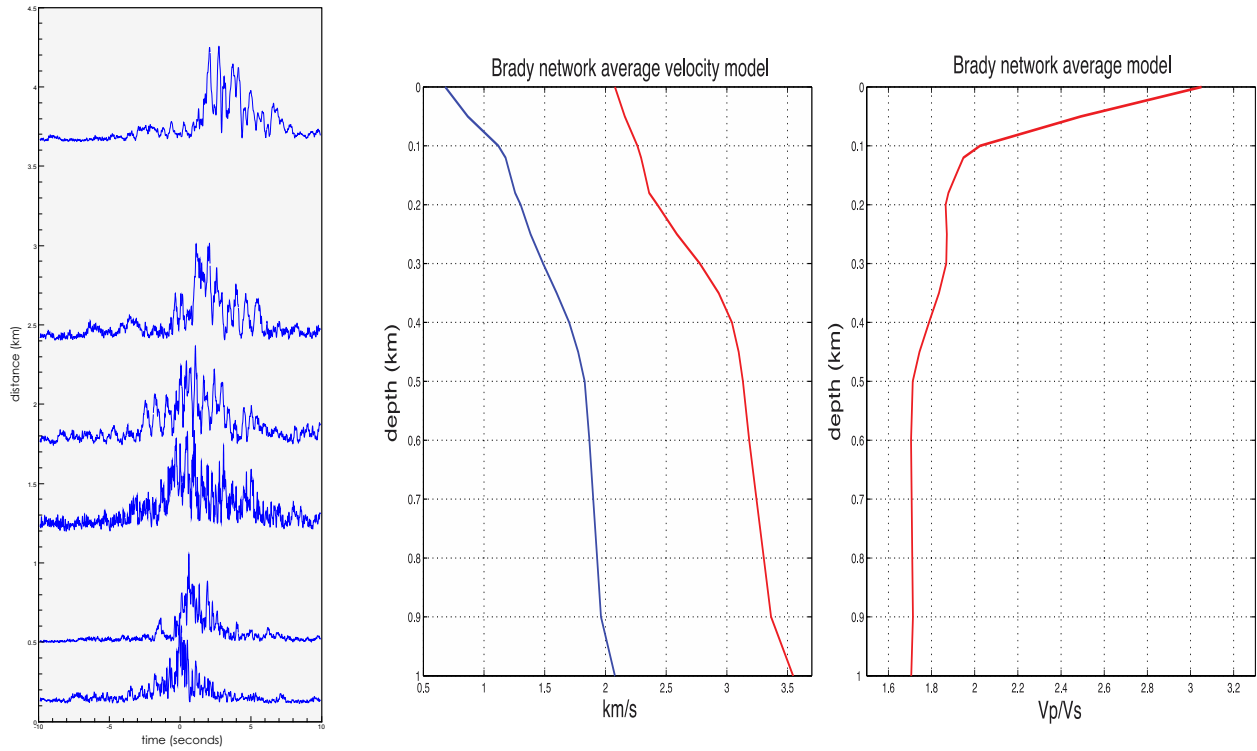


**Figure 1: Coverage maps of the Brady Hot Springs. (Left) The LBL seismic stations (green triangles) lie just south and west of the natural lab. Interferometry allows us to measure the physical properties along paths connecting each pair of seismic stations (blue). (Right) Focusing in on the natural lab site: 238 geophones (red triangles) recorded data during the 15 days of the experiment. The coverage between elements of the natural lab is significantly denser than that of the permanent array.**

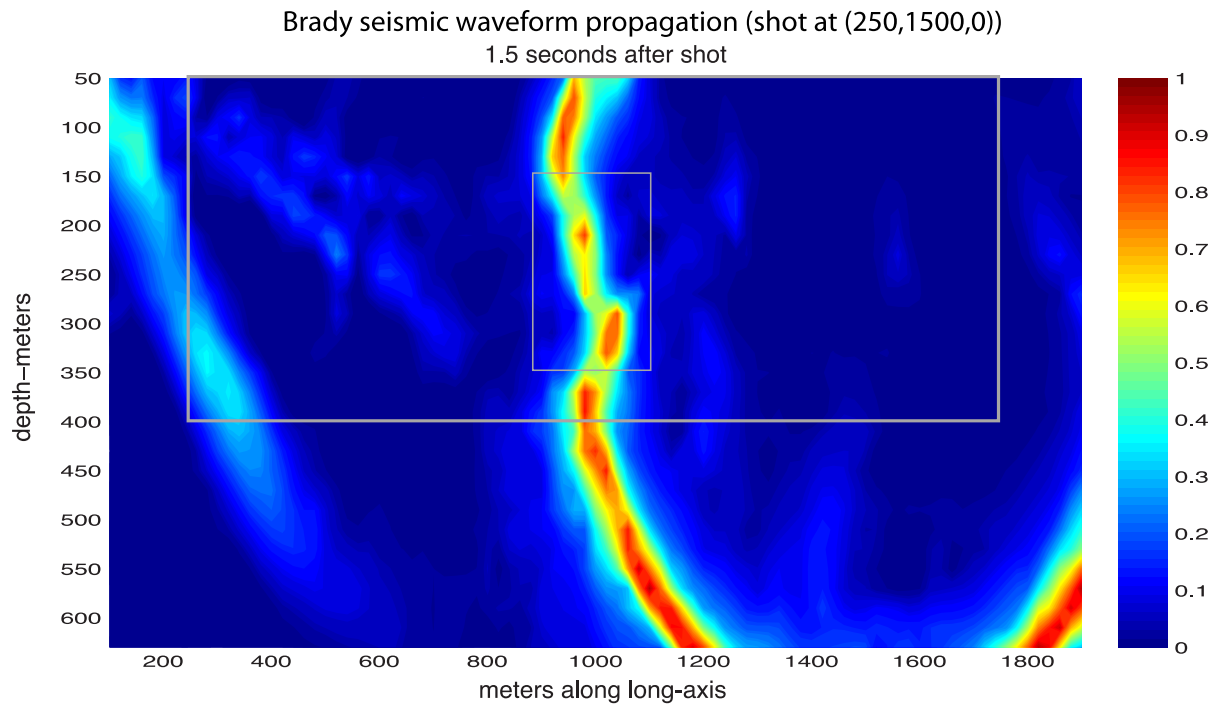
The PoroTomo site is a 1500-by-500 meter natural laboratory at an EGS field operated by Ormat (figure 1). It lies just north of an existing seismic network run by Lawrence Berkeley Lab (LBL) and adjacent to highway I-80. The LBL network includes 16 three-component 4.5 Hz seismometers sampling continuously at 500 Hz. Prior to the deployment of the PoroTomo geophone network, we collected 3 months of continuous data recorded at the LBL network to test the effectiveness of using the ambient noise methodology in the region. During the PoroTomo deployment, 238 three-component geophones were installed at the Brady. We used several sources of energy in our analysis: the ambient background wavefield, traffic noise from the highway, and records of the vibroseis sweeps. The resolution in depth is determined by the longest distance between instruments. Lateral resolution is determined by the spacing between the instruments and the number of inter-station paths crossing a given point.

Using data from the LBL network, we are able to obtain high SNR Green's functions with as little as 24 hours of recorded data. When the full data set is included we recover high SNR up to 30 Hz. Based on this data set, we created a preliminary seismic velocity model of the site, which allowed us to predict the lateral and depth resolution we could expect from the experiment. The large network at the natural lab increases lateral resolution by more than three orders of magnitude. At the LBL network, 16 active seismometers gave us 120 unique paths over an area of roughly 7.5 km<sup>2</sup>. At the natural lab, using data from the 238 geophones, we obtained 28,203 unique paths sampling an area of 1.5 km<sup>2</sup>. At the LBL network we are able to measure variability in the subsurface to depths exceeding 2 km. The PoroTomo resolution extends to depths of several hundred meters.

Because the PoroTomo network was only in place for 15 days, the resulting GF are noisier, particularly at offsets larger than 500 m, but we are still able to obtain GF up to 30 Hz in most cases. We inverted the waveforms to obtain seismic velocities and see large variability. At 50 m,  $V_s$  ranges between 400-650 m/s and the  $V_p/V_s$  ratio varies between 3 and 4. The variations in  $V_p/V_s$  appear to be associated with faults in the subsurface.



**Figure 2: (Left) Envelopes of ambient noise correlation Green functions acquired at the LBL array. (Center) The average seismic velocity model based on the LBL data. (Right) Measured  $V_p/V_s$  ratio increases rapidly in the top 100 meters.**



**Figure 3: Simulated waveform propagating through the LBL model for a source at one of the vibroseis sweep points. The outline of the PoroTomo natural laboratory extends to 400 meters depth. A low velocity anomaly at depth in the center of the site was used to estimate effective resolution.**

### 3. CONCLUSIONS

The Poroelastic Tomography experiment (PoroTomo) allowed us to test several techniques of seismic interferometry. Ambient noise correlation is precise but computationally expensive. Sweep interferometry is fast, but not as easily reproducible. The dense network, recording for 15 days provided enough data for us to calculate high SNR Green's functions, which we use to image subsurface structure. The natural lab has highly heterogeneous material properties, with seismic velocities dropping rapidly in the top 100 meters coupled with a rapid increase in  $V_p/V_s$ .

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