Imaging the Newberry EGS Site using Seismic Interferometry

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ABSTRACT
A natural response to fluid injection is the creation of microseismicity. Often thousands of microquakes are associated with an injection well. These microquakes effectively illuminate the subsurface, allowing us to monitor plume growth and identify previously hidden faults. In order to take full advantage of these data, precise seismic measurements on these microquakes is key. An essential component of microseismic processing is an accurate seismic velocity and attenuation model for the formation. We need a detailed image of the Earth from the surface, where the instruments are located, to a depth below the zone of microseismicity.

In this study, we demonstrate the power of seismic interferometry for use in geothermal studies. First, we apply ambient noise correlation (ANC) to dozens of seismic stations in and surrounding the Newberry geothermal site, which provide hundreds of unique paths sampling the region. We demonstrate that we can use a mix of instruments and networks to maximize resolution laterally and with depth. We inverted for the best 1D models along each path and created a 3D model based on those results. Synthetic seismograms calculated through the 3D model capture the complexity of the direct and scattered waves that are observed in microquake data.

1. INTRODUCTION
The correlation of ambient seismic noise is a rapidly developing field of seismology. One of the techniques included in the field of seismic interferometry, it is based on the observation that the Earth's background noise (generated in part by ocean waves, distant earthquakes and multiply scattered coda) includes coherent energy, which can be recovered by observing over long time periods and allowing the incoherent energy to cancel out (Hennino et a., 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). This means that many of the techniques developed in earthquake seismology can be applied directly to the correlations.

A major advantage of the noise-correlation technique is that it strips away dependence on earthquakes or artificial sources for a solution. Problems of source location and velocity heterogeneities outside the region of interest are no longer present, as only the structure between the station pair contributes to the signal. In particular, it allows high resolution imagery beneath dense seismic networks even in areas of low seismicity. The energy in the correlated waveforms is also quite high in frequency bands which are particularly sensitive to the Earth's crust. ANC does require long, preferably continuous data records as the Green's function emerges from the incoherent noise.

To date, most ANC research has focused on group velocity measurements of the resulting surface waves (Moschetti et a., 2007; Shapiro et al, 2005) although more recently, work has begun on measuring the phase velocities (Lin et al, 2008) and amplitudes (Prieto and Beroza 2008; Snieder and Safak, 2006; Matzel, 2008) and the new discoveries and methodologies are constantly being developed.

In this study, we use ANC to image the site of the Newberry EGS experiment down to 5 km. Our intent is to precisely locate and monitor the microseismicity associated with fluid injection. We collected continuous data for the month of October 2012, for the 22 stations in the Newberry network, together with 12 additional stations from the nearby CC, UO and UW networks. The data were instrument corrected, whitened and converted to single bit traces before cross correlation according to the methodology laid out in Benson (2007). There are 231 unique paths connecting the 22 stations of the Newberry network. The additional networks extended that to 402 unique paths crossing beneath the Newberry site.

Because we are particularly interested in the very shallow seismic structure, we need high quality correlation waveforms at frequencies from 0.5-15 Hz. These particular data are very good and the Green's functions (GF) emerge quickly. We treated each GF as a seismic record and inverted for the best fitting 1D model along each path. The objective was to maximize the fit between the GF and synthetic seismograms, including the scattering energy in the coda. Short paths and high frequencies are most sensitive to the shallowest structures. Deeper structures are resolved using longer paths.

We inverted simultaneously for Vp, and Vs and Qs, although Qs is poorly resolved. We broke the data into 3 groups. GFs for paths shorter than 5 km were filtered between 0.6 to 15 Hz and focused on matching details to 1 km. For paths between 5 - 10 km we filtered GFs between 0.5-8 Hz and data for the longest paths were filtered between 0.1 - 2 Hz. These longest paths, typically including at least one station outside the Newberry network, extended our coverage laterally and to depths below 5km. The
individual 1D models were merged into a tomogram of the region using singular value decomposition. Slices through the final 3D model are presented in figure 1. The seismicity generally follows the most rapid changes in velocity gradient. To test the accuracy of our result, we calculated synthetic seismograms for local earthquakes through both the original reference 1D and final 3D models using the reflectivity method and the LLNL SW4 code, respectively.

We compare the synthetics to a M1.85 earthquake that occurred on December 1, 2012. The 1D synthetics are only able to capture one or two peaks of the actual wavetrain (figure 2, left). The 3D synthetics capture the complexity of the direct and scattered waves, such as those observed at the NB19 surface station (figure 2, right). Finally, we compare the rate of microearthquake occurrence with the fluid injection and pressure parameters. We apply the Matched Field Processing (MFP) method to identify more and smaller microearthquakes than were identified using traditional STA/LTA earthquake detection methods. Between October – December 2012, 204 events were identified using traditional techniques. In the same 3 months the MFP technique identified 249 additional events.

Figure 1: Slices through the shear velocity model at 0.5 and 2.0 km depth, including the independently located seismicity (cyan circles). Continuous data from Newberry network stations (blue triangles) and nearby seismic networks (off map) were used to constrain the velocity structure beneath the site down to 5 km.
2. CONCLUSIONS
Seismic interferometry is a powerful tool for characterizing the shallow subsurface. At the Newberry EGS site, we are able to recover high quality Green’s functions, with only a few weeks of data. This is rapid enough that it can be used to monitor changes at the site over time. We can resolve sharp variations in both P and S velocity throughout the zone of microseismicity. Precise 3D models allow us to precisely locate the microquakes and monitor the plume growth as injection proceeds.

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