PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

Measuring the Material Properties Beneath Geothermal Fields Using Interferometry

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Keywords: Salton Sea, geothermal, microseismicity, seismic interferometry, tomography

ABSTRACT

Microseismicity provides a direct means of measuring the physical characteristics of faults and fractures beneath geothermal sites. Hundreds to thousands of small earthquakes often occur during operations. This seismicity helps define the active zone, allowing us to measure structural properties of the geothermal field. Here, we focus on two methods of seismic interferometry, ambient noise correlation (ANC) and the virtual seismometer method (VSM). 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. 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, the Green function (GF). The calculation of the GF is often stable after a few weeks of continuous data correlation, any perturbations to the GF after that point are directly related to changes in the subsurface and can be used for 4D monitoring. VSM is a style of seismic interferometry that provides fast, precise, high frequency estimates of the GF between earthquakes. VSM illuminates the subsurface precisely where the pressures are changing and can monitor the evolution of the pressure field over time. With hundreds of earthquakes, we can calculate thousands of waveforms. At the same time, VSM collapses the computational domain, often by 2-3 orders of magnitude. This allows us to do high frequency 3D modeling. These methods allow us to estimate material properties, including absolute seismic velocities, Poisson's ratio, and seismic attenuation. When sufficient data are collected, we can also estimate changes in those properties over time.

1. INTRODUCTION

In seismology, the Green function (GF) is defined as the response of the Earth at one point due to an impulsive source at another. In simple terms, GFs are the data recorded by seismometers once the peculiarities of the source and instrument are removed. Because of reciprocity, the seismic record would be the same even if the locations of the impulsive source and the seismometer were switched. In recent years, seismologists have used this principle in the emerging field of seismic interferometry to treat seismometers as virtual earthquakes and earthquakes as virtual seismometers.

In 2003, Campillo and Paul used the cross correlation of the scattered energy that arrives after an earthquake (called the coda) recorded at different seismic stations to obtain the GF of the Earth between the stations (Campillo and Paul, 2003). Since then, the field of seismic interferometry has rapidly expanded and produced highly detailed images of the crust and upper mantle. Seismic interferometry has often focused on using the ambient noise field to obtain image the interior of the Earth between pairs of stations. However, it is straightforward to flip the geometry used by Campillo and Paul and focus instead on the structure between pairs of earthquakes. Hong and Menke (2006) took advantage of this theory to study wear along the San Jacinto fault. The theory was developed more completely by Curtis et al. (2009), who demonstrated that you can convert earthquakes into "virtual seismometers" by using the correlation properties of records from distant arrays.

1.1 Ambient noise correlation (ANC)

Ambient noise correlation takes advantage of the fact that the Earth's background noise includes coherent energy, which can be recovered by observing over long periods of time, 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 and Safak, 2006; Wapenaar, 2004). When applied to a dense seismic network, each seismometer can be treated as a "virtual earthquake" recorded by all the others. Unlike natural earthquakes, the origin time and locations are perfectly known, and the effective source mechanism is very simple. This allows high resolution imagery even in areas of low seismicity.

Here we illustrate the precision with which ANC can image shallow seismic structure. We collected continuous data from 54 stations in Southern California, with a focus on the geothermal fields at the Salton Sea. We included 2 months of continuous data from the EN and CI networks. The data were processed according to the methodology laid out in Benson (2007). We inverted simultaneously for Vp, and Vs and Qs. We broke the data into 3 groups. GFs for paths shorter than 10 km were filtered between 0.5-8 Hz and focused on resolving structure shallower than 5 km. Data for the longest paths were filtered between 0.1 - 2 Hz. These longest paths extend coverage laterally and to depths throughout the crust. Figure 1 illustrates the quality of the virtual seismograms obtained, and the details resolved by the 3D tomography. Filtering the image at high spatial frequency illuminates fault-like structures that are highly correlated with the independently catalogued seismicity in the region (Hauksson et al., 2011).

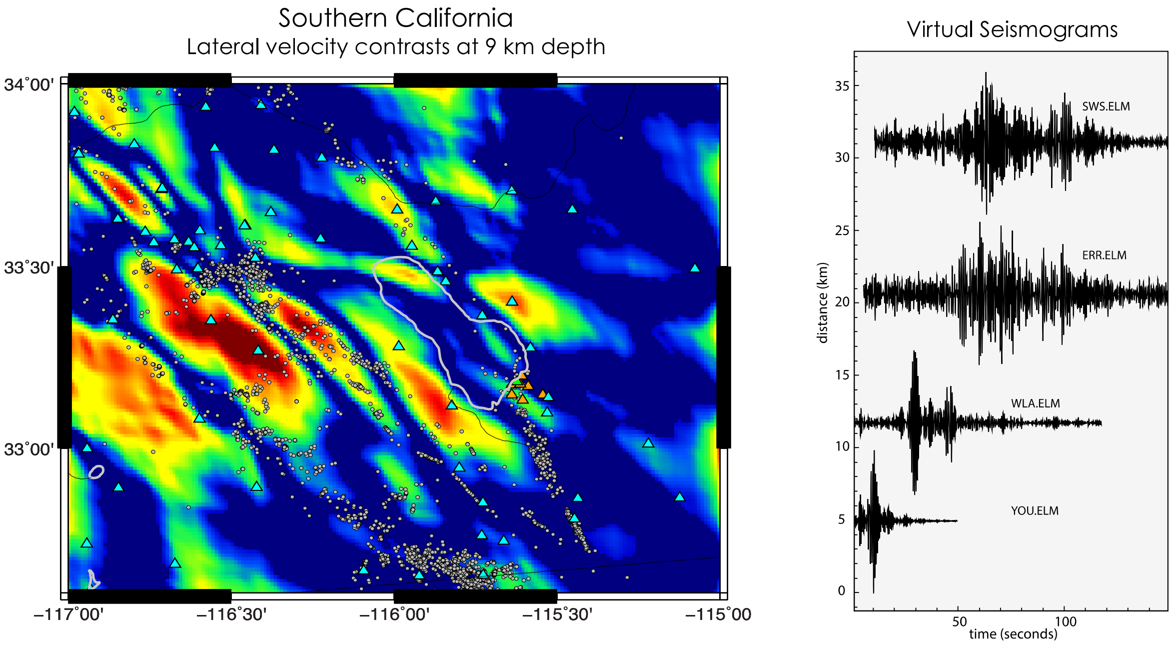

Figure 1: ANC tomography of the Salton Sea region in Southern California. (Left) High frequency filter of the model in the spatial domain at 9 km depth illuminates faults. Seismic stations are plotted as triangles, catalogued seismicity from Hauksson et al. (grey circles). (Right) ANC virtual seismograms used in the inversion.

1.2 Virtual Seismometer Method (VSM)

The Virtual Seismometer Method (VSM) is a technique that provides precise estimates of the GF between earthquakes (Curtis et al., 2009; Hong and Menke, 2006). In simple terms VSM involves correlating the record of a pair of events recorded at an individual station and then stacking the results over all stations to obtain the final correlation waveform. By effectively replacing each earthquake with a "virtual seismometer" recording all the others, the technique isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features where seismic stations either can't or haven't been located, such as at depth in active fault zones.

In the far-field, when most of the stations in a network fall along a line between two earthquakes, the result of the correlation is an estimate of the GF between the two, modified by the source terms. In this geometry each earthquake is effectively a virtual seismometer recording all the others. Even when two earthquakes line up at an angle to the recording network, the effects of the geometry can be removed before stacking to obtain the GF estimate. However, in microseismic systems, the uncertainty in location and origin time are compounded by the fact that the distance between individual stations in the recording network may be much farther from one another than they are from the zone of microseismicity and the effects of geometry become more pronounced.

When VSM is applied to microseismic data we are typically working in the very near field, where the distance between microquakes can be larger than the distance from an individual microquake to elements of the recording network. At this range, microquakes often fall within each other's uncertainty ellipse. The spectrum of the calculated signal is defined by the recorded seismicity and we can obtain very high frequency estimates of the Green functions using this technique.

We apply the VSM to data from the Salton Sea geothermal region in an effort to refine our image of the subsurface. Thousands of small earthquakes occur beneath the geothermal fields, enabling the potential for millions of measurements. We subdivided the data using 183 well characterized template events and related events detected using Matched Field Processing (Wang et al., 2015). Virtual seismograms are calculated by correlating roughly 20 seconds of the coda of each event record. This results in over 16,000 correlations, 1500 of which have optimal geometry. The symmetry and structure of the correlation waveforms allow us to refine the locations in space and measures of amplitude and arrival times help us resolve structural anomalies in the active region.

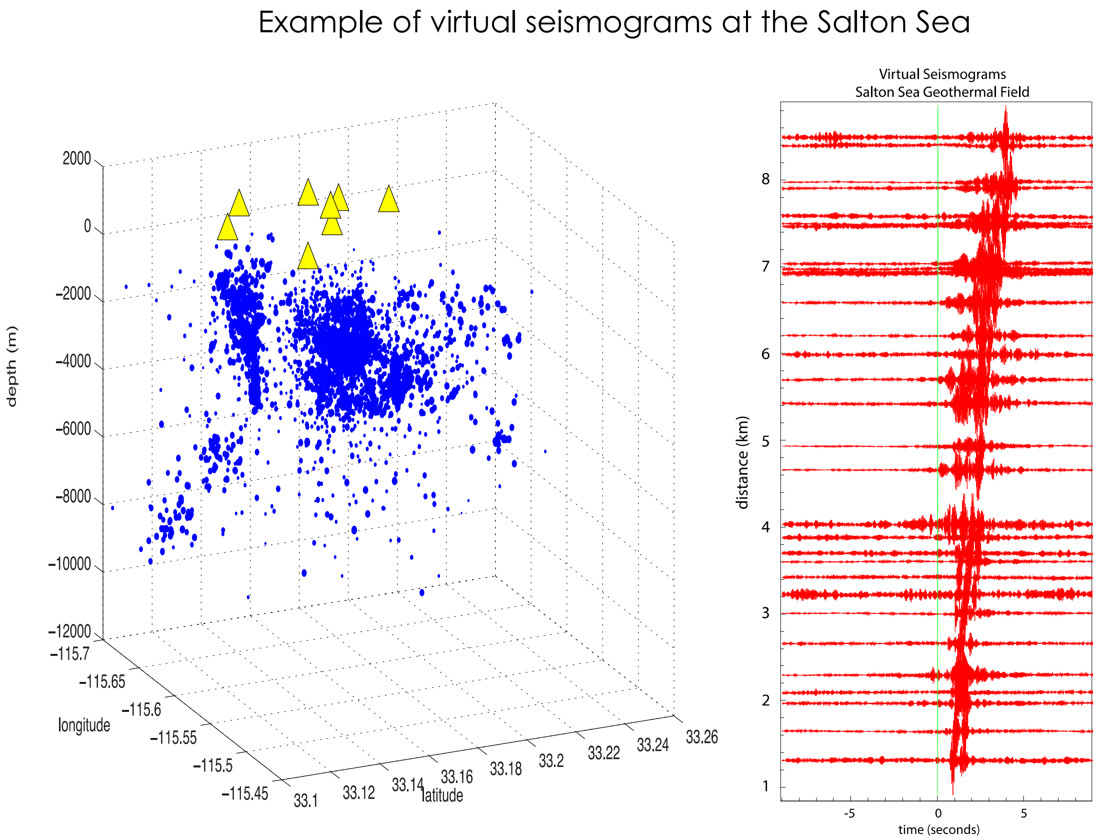

Figure 2: (Left) Thousands of catalogued microseismic events (blue) occur beneath the Salton Sea geothermal fields and are recorded by the local seismic network (yellow triangles). (Right) Virtual seismograms calculated using the microseismic records. Seismicity from Hauksson et al. (2011)

2. CONCLUSIONS

Microseismicity is closely associated with geothermal development and can be used to monitor the evolution of the pressure field due to fluid injection. Seismic interferometry can be used to create detailed images of the subsurface precisely where the pressures are changing. We apply both “virtual earthquake” and “virtual seismometer” techniques help image material properties, particularly Vp, Vs and attenuation, in the Salton Sea geothermal region.

In many ways, VSM is the converse of ANC. VSM is very fast, only a few minutes of data are needed, compared to the weeks to years of continuous data often required for ANC. Furthermore, the GF obtained by VSM have the same high frequency content as the microearthquakes, while the spectrum of ANC is determined by the lower frequency natural background noise. For microseismic studies, this allows us to obtain very high frequency estimates of the GF between microquakes. Both techniques gain power rapidly as more elements are added to the system according to the equation $N*(N-1)/2$. For ANC, these elements are the individual seismometers, for VSM the elements are the individual earthquakes. The key strength of ANC is that timing and location of the elements are perfectly known and the GF is equivalent to that of a simple impulsive source. For VSM, neither the timing nor the location of the elements is known and the correlation waveform is the GF, modified by both moment tensors. For this reason, ANC is quite sensitive to the heterogeneities in the Earth structure, while VSM is most sensitive to the source parameters, which need to be accounted for before Earth structure can be recovered.

This work was supported by the Geothermal Technologies Office (GTO) of the U.S. Department of Energy through contract DE-AC52-07NA27344 to Lawrence Livermore National Laboratory.

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