Exploring Temporal Variability in Seismic Velocity at the Salton Sea Geothermal Field and its Implication for Induced Seismicity

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I. Project Overview

A. Abstract

We search for velocity changes associated with activities of the geothermal energy development at the Salton Sea Geothermal Field. The noise cross-correlation functions (NCFs) are computed for ~6 years of continuous three-component seismic data (December 2007 through January 2014) collected at 8 sites from the CalEnergy network. Velocity changes \((dv/v)\) are obtained by measuring time delay between 5-day stacks of NCFs and the reference NCF (average over the entire 6 year period). The time evolution of \(dv/v\) exhibits two types of velocity changes. The first type of velocity change is sudden reductions and the other one is a long-term increase. A notable velocity drop is observed in the beginning of April 2010. The onset time of this temporal reduction is correlated with the occurrence of the 4 April 2010 \(M_w 7.2\) El Mayor-Cucapah earthquake. The level of velocity reduction is gradually increased with decrease of the frequency. The largest reduction (0.25\%) is observed in the frequency band, 0.5-2.0 Hz. Assuming coda of NCFs are mainly composed of scattered surface waves, the \(dv/v\) change was likely occurred in a depth of \(~1.0\) km depth. The second type of velocity change is a long-term velocity increase. As with the sudden velocity reductions associated with earthquakes, the long-term increase in velocity displays clear frequency dependence. The larger velocity increase was identified in lower frequency bands. An increase in velocity of \(~0.3\%\) was found in the 0.5-2.0 Hz band during a 6-year period, which corresponds a 0.05%/year increase in velocity.

B. SCEC Annual Science Highlights

Seismology, Stress and Deformation Over Time (SDOT), Collaboratory for the Study of Earthquake Predictability (CSEP)

C. Exemplary Figure

Figure 2 of the Technical Report. Figure caption (from the report): Temporal evolution of seismic velocity \((dv/v)\) with five different frequency bands. EMC and BS represent the 2010 \(M_w 7.2\) El Mayor-Cucapah earthquake and 2012 Brawley seismic swarm.

D. SCEC Science Priorities

2f, 2c, and 2d

E. Intellectual Merit

This project relates to several SCEC objectives related to the induced seismicity and will advance our knowledge of the behavior in the geothermal reservoir dynamics at the Salton Sea Geothermal Field. In particular, our time history of seismic velocity change provides additional insights into the relationships between the geothermal operation and the long-term velocity change at the Salton Sea Geothermal Field.
F. Broader Impacts

This project documents the temporal variability of seismic velocity at the Salton Sea Geothermal Field by systematically analyzing ~6 year of continuous seismic data with seismic interferometry. A student involved in this project is actively participating in the SCEC annual meeting with the travel support from this project. The project also supported to foster an international collaboration with colleagues from France.

G. Project Publications


II. Project Overview

A. Introduction

A rapid growing interest in renewable energy has been substantially advanced renewable technologies and energy efficiency in the last decade. Geothermal is one of valuable global resources in the renewable energy development and has been playing an important role in supporting the global energy requirement [Majer et al., 2007]. The Salton Sea geothermal field (SSGF) located in the Salton Trough of southernmost California is one of the largest geothermal reservoirs in the world and is marked by hot fluid with ~350°C in a depth of 2 km. Operations at the SSGF commenced in 1980s and include 10 operational geothermal plants that extract and inject water in a depth of 1-3 km. The SSGF experiences intense seismicity associated with the geothermal development. Brodsky and Lajoie [2013] suggests the net fluid volume (subtraction total fluid injection from total fluid withdrawal) controls the background seismicity at the SSGF.

Geothermal-induced earthquakes have been observed at other geothermal plants [Majer and Peterson, 2007; Megies and Wassermann, 2014] and have heightened public awareness in the last several years. There is an urgent need for continuous monitoring of the geothermal reservoir to identify changes in reservoir characteristics that might induce earthquakes. Seismic interferometry with ambient noise has become the most powerful seismological approach to continuously monitor temporal behaviors of fluid in the Earth’s interior [e.g., Brenguier et al., 2008b, 2016; Taira and Brenguier, 2016]. There is, however, a few studies that applied ambient noise based imaging technique to identify time-dependent geothermal reservoir characteristics [Hillers et al., 2015; Obermann et al., 2015]. Also those studies focused on about one-year data. We here systematically explore changes in seismic velocity at the SSGF by analyzing ~6 year of continuous seismic recordings with seismic interferometry.

B. Ambient Noise Cross-Correlation

The temporal behaviors of seismic velocity at the SSGF were determined through temporal variation in noise cross-correlation functions (NCFs) obtained from seismic records collected at the eight stations of the CalEnergy network (Figure 1). Each EN station is equipped with a three-component short period (4.5 Hz) geophone (Mark Products L15B) and seismic data are sampled at 100 Hz. The interstation distance ranges from 2.3 km to 10 km. All available seismic data (December 2007 through January 2014) were extracted from the Southern California Earthquake Data Center [SCEDC, 2013]. No seismic waveform collected after January 2014 is available to public [Ellen Yu, personal communication, 2015]. To address depth variation in seismic velocity, NCFs were computed with six different frequency bands (0.25-0.1, 0.5-2.0, 0.75-3.0, 1.0-4.0, 1.5-6.0, and 2.0-8.0 Hz) by MSNoise software [Lecocq et al., 2014].
Our data process for obtaining NCFs is similar to those in Brenguier et al. [2008b] and Taira et al. [2015]. First the instrument response was corrected on 1-day-long continuous seismic data to obtain ground displacement, and then a bandpass filter between 0.08 and 8.0 Hz was applied. Daily bandpassed waveforms were down-sampled into 20 Hz and split into 30 minute-long-data. To suppress seismic signals associated with local and teleseismic earthquake signals, a spectral whitening process and subsequently one-bit normalization were applied at frequency bands of interest. The NCFs were computed for all station pairs in the 9 different combinations of components (e.g., vertical-vertical, vertical-north, and north-east). Daily NCFs were obtained from stacking NCFs with 30 minute-long-data. NCFs with good signal-to-noise ratio were not recovered in the lowest frequency range, 0.25-0.1 Hz and were excluded from the further analysis.

Temporal variation in seismic velocity ($dv/v$) was determined through the time delay measurement ($dt$) for a pair of NCFs with the moving window cross-spectral technique [Clarke et al., 2011], assuming a homogenous velocity change which predicts $dv/v = - dt/t$ [Brenguier et al., 2008; Wegler et al., 2009]. The $dv/v$ was obtained from $dt$ between the 5-day stack of NCFs and reference NCFs averaged over the whole ~6-year period. Coda of NCFs were used for the $dv/v$ measurement to minimize the bias due to variability of noise source over time and space [Paul et al., 2005; Stehly et al., 2006]. The starting time of NCF coda ($t_s$) was determined based on interstation distance ($D$), $t_s = D/0.3$ that corresponds to about 6 times of direct surface-wave arrival time assuming with 2 km/s for the surface (Rayleigh and Love) wave velocity. The length of the coda window is 20 seconds. There are a number of time periods (about several weeks) in which values of cross-correlations between 5-day stack of NCFs and reference NCFs were dropped. The continuous seismic recordings were manually checked. It appears that sensors did not work appropriately during those time periods. The time history of $dv/v$ was computed by averaging $dv/v$ measurements over all channel pairs (252 pairs) in the five frequency bands (0.5-2.0, 0.75-3.0, 1.0-4.0, 1.5-6.0, and 2.0-8.0 Hz) (Figure 2).
Figure 2: Temporal evolution of seismic velocity ($dv/v$) with five different frequency bands. EMC and BS represent the 2010 $M_w$ 7.2 El Mayor-Cucapah earthquake and 2012 Brawley seismic swarm.

C. Temporal Evolution of Seismic Velocity

The time evolution of seismic velocity ($dv/v$) exhibits two types of velocity changes (Figure 2). The first type of velocity change is sudden reductions and the other one is a long-term increase. A notable velocity drop is observed in the beginning of April 2010 and is registered in all frequency bands except for the lowest frequency range, 0.25-1.0 Hz. The onset time of this temporal reduction is correlated with the occurrence of the 4 April 2010 $M_w$ 7.2 El Mayor-Cucapah (EMC) earthquake (the location of the EMC hypocenter shown in the inset in Figure 1). The level of velocity reduction is gradually increased with decrease of the frequency (Figure 3a). The largest reduction (0.25%) is observed in the frequency band, 0.5-2.0 Hz. Assuming coda of NCFs are mainly composed of scattered surface waves, the $dv/v$ change was likely occurred in a depth of ~1.0 km depth (Figure 4). Note however that our data does not have capability of exploring velocity changes below 3.0 km because of the poor signal-to-noise ratio of NCFs below 0.5 Hz.

There appears to be another velocity reduction in the end of August 2012 in which the 2012 Brawley seismic (BS) swarm occurred 15 km south of the SSGF (the figure inset in Figure 1). This swarm consists three $M$~5 earthquakes occurring on August 26, 2012 and an elevated earthquake activities (over 600 earthquakes) lasted about 1 month [Hauksson et al., 2013; Wei et al., 2015]. A frequency-dependent velocity change was observed (Figure 3b) in which the velocity reduction tends to be increased in lower frequency bands. About 0.1% velocity drop was yielded in 0.5-2.0 Hz, 0.75-3.0 Hz, and 1.0-4.0 Hz bands whereas velocity reduction of 0.05-0.07% was obtained in the 1.5-6.0 Hz and 2.0-8.0 Hz bands.
Figure 3: Enlarged views of temporal evolution of seismic velocity ($dv/v$) for (a) EMC earthquake and (b) BS swarm.

The second type of velocity change is a long-term velocity increase. A steady increase in velocity was observed over the entire analysis period (Figure 2), although this long-term velocity increase was interrupted by earthquake-induced velocity reductions and might include increases in velocity associated with post-seismic recover processes. As with the sudden velocity reductions associated with earthquakes, the long-term increase in velocity displays clear frequency dependence. The larger velocity increase was identified in lower frequency bands. An increase in velocity of ~0.3% was found in the 0.5-2.0 Hz band during a 6-year period, which corresponds a 0.05%/year increase in velocity. On the other hand, the high-frequency $dv/v$ time series shows a weak long-term velocity increase (0.017%/year).

Figure 4: Frequency-dependent Rayleigh surface-wave sensitivity to velocity perturbations that constitute a proxy for depth resolution. The surface-wave sensitivity kernel for each frequency was computed with the one-dimensional (1D) S-wave velocity model was derived from the 1D P-wave velocity model from Holland (2002, MS. Thesis, the University of Texas at El Paso) assuming with $V_p/V_s=1.73$. Computer Programs in Seismology package [Herrmann, 2013] was used to the sensitivity kernel estimate.

D. References


Brenguier, F., D. Rivet, A. Obermann, N. Nakata, P. Boué, T. Lecocq, M. Campillo, and N. M.


