Seismic Signature of the Geothermal Field at Soda Lake, Nevada, from Ambient Noise Analysis

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Keywords

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ABSTRACT

Our objective is to estimate geothermal reservoir indicators, such as: P and S seismic velocity models to a depth of ~300 m, ambient noise spectral energy and media stochastic properties. An important advantage of our method is estimating the shear velocity model, which, unlike the P-velocity model, is not yet accomplished by conventional reflection surveys. We analyze ambient seismic noise recorded by a 3 day, 1.3 km^2, 100 m spaced vertical geophone survey as well as four 12 m-separation seismic lines. The survey was conducted by UNR and Imageair Inc. in March 2010 at Soda Lake, Nevada, geothermal field operated by Magma Energy Corporation.

We use seismic interferometry, a new imaging method, to generate subsurface images without any larger seismic sources, such as explosions or earthquakes. One application of seismic interferometry is to retrieve the impulse response or Green's Function (GF) from crosscorrelation of ambient seismic noise. The ambient-noise autocorrelation at each station is interpreted as the collocated source–receiver elastic wave Green's Function (i.e. the Earth's reflection response).

Stacks of ambient noise crosscorrelations at pairs of sensors over three days result in inter-station GF's, with Rayleigh waves as dominant arrivals. A preliminary estimation of the velocity of phases which we interpret as fundamental Rayleigh waves shows lower surface wave velocity and higher scattering within the geothermal production field, at frequencies of 1-5 Hz. Using array processing techniques, such as frequency-wavelength (fk) analysis, we will estimate Rayleigh-wave phase velocity dispersion curves. The dispersion estimates will be inverted for surface wave velocity models using the Computer Programs in Seismology (CPS3.0) surf96 algorithm. Stacks of autocorrelations of ambient noise data recorded at individual sensors result in retrieval of the Earth's reflection response at the location of each sensor. The autocorrelation traces are interpreted in terms of reflection GF phase composition and crustal reflector properties. By applying crosscorrelation to ambient noise data recorded at pairs of sensors located 12 m apart we generate virtual shot gathers as if one of the sensors is generating seismic waves, i.e. we retrieve the Earth's reflection response.

We will also investigate whether differences between production and non-production geothermal reservoir areas could be assessed by measuring seismic scattering. We will compare the stochastic parameters (Hurst number, characteristic length) from the ambient noise autocorrelations and crosscorrelations and the ambient noise spectral energy differences above the geothermal reservoir to similar parameters outside the geothermal reservoir area.

Figure 1. Google Earth map showing Soda Lake and study area (yellow square).

Introduction

We report work in progress for the development of a new, cost-effective method, based on ambient seismic noise analysis, to estimate geothermal reservoir indicators such as: P and S seismic velocity models to a depth of ~300 m, ambient noise spectral energy and media stochastic properties at the location of a geothermal exploration area operated by Magma Energy Corporation, near Soda Lake. An important advantage of our method is estimating the shear velocity model of the Soda Lake geothermal field, which, unlike the P-velocity model, is not accomplished by conventional reflection surveys.

Soda Lake is one of many geothermal systems hosted in the extensional Basin and Range Province, Nevada. This geothermal field is located about 100 km east of Reno and 10 km northwest of Fallon (Figure 1), along the Carson River Route of the Old California Trail (Figure 2). Soda was mined from Soda Lake in the middle to late 19th century. There might have been a hot spring discharging at that time as well (Hill et al., 1979). Soda Lake was identified as a geothermal resource in 1903 while drilling for a water well, which reached boiling water at depth of 18 m. This well was still emitting hot steam in 1974, while shallow subsurface boiling was indicated by alteration of Quaternary sediments to kaolinite and various iron oxides or hydroxides (Olmsted et al., 1975). The extent of the thermal anomaly in the shallow subsurface has been outlined by the drilling of temperature-gradient holes by the U.S. Geological Survey and the U.S. Bureau of Reclamation, as well as continued drilling of production, injection and monitoring wells. The hottest parts of the Soda Lake thermal anomaly probably coincide with intersection of faults trending north-northeast and northwest. These faults provide steeply inclined conduits for thermal fluids that may be rising from depths 3 to 7 km (Olmsted et al., 1984). Although faults exposed on the surface are rare, some faults at depth were suggested, possibly along a rupture zone in the Tertiary or pre-Tertiary consolidated rocks (Olmsted et al., 1975).

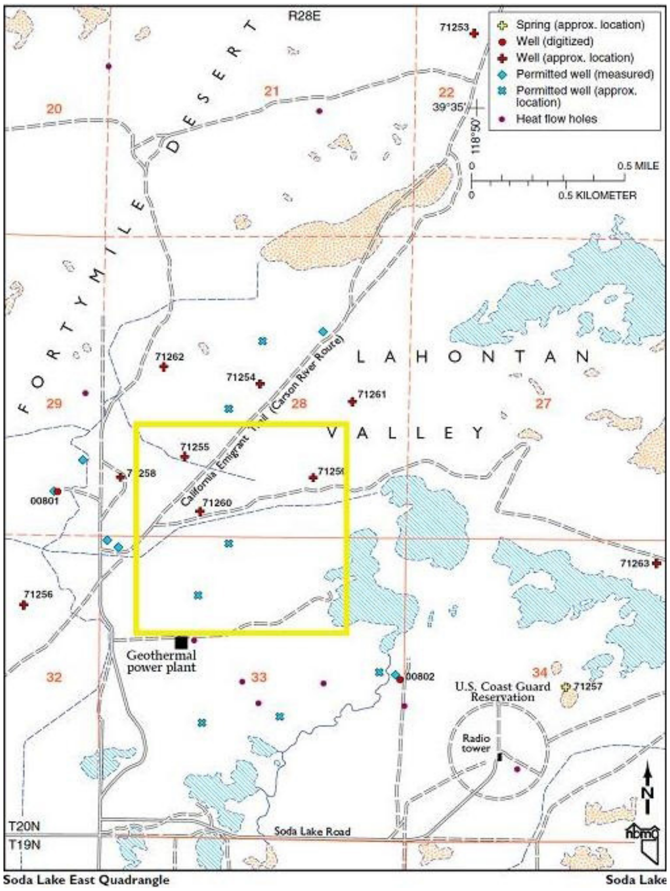

Figure 2. Map of Soda Lake area (from http://www.nbmg.unr.edu/geothermal/). Yellow square outlines study area.

Two binary plants came on-line at the Soda Lake geothermal field in 1987 and 1991. Their gross installed capacity is 23.1 MW, with estimated net capacity ~16 MW. However, when Magma Energy (US) Corp. acquired them in 2008, the annual output was averaging only 8 MW (Van Gundy et al., 2010). Therefore a major task was to restore the nameplate capacity and increase power production. A comprehensive 3D geophysical model of the geothermal field was created using various data that were collected and analyzed together for the first time, such as geological maps, locations and depths of wells, mud-logging and drilling data, temperature surveys, geophysical logs, LiDAR, resistivity, magnetic anomalies, microgravity, old seismic studies, etc. In addition, in June 2010 a 3D, three-component reflection seismic survey was carried out and is being integrated with existing well and precision gravity data (Echols et al., 2011).

One result of these investigations was the discovery of a steam cap (Van Gundy et al., 2010). In January 2010 a flow test of a former producing well (41-33) dramatically demonstrated that a steam cap had developed beneath it. The location of the steam cap was associated with contours (Figure 3) marking the largest subsidence indicated by Interferometric Synthetic Aperture Radar using Satellite Imagery (InSAR). The maximum subsidence in the field approaches 2 cm/year and the size of the total subsidence area is significantly larger than the area outlined by the contours shown in Figure 3 (Gary Oppliger, personal communication). The InSAR anomaly marks the hottest and shallowest part of the field. The elevated temperatures actually cover an area with a

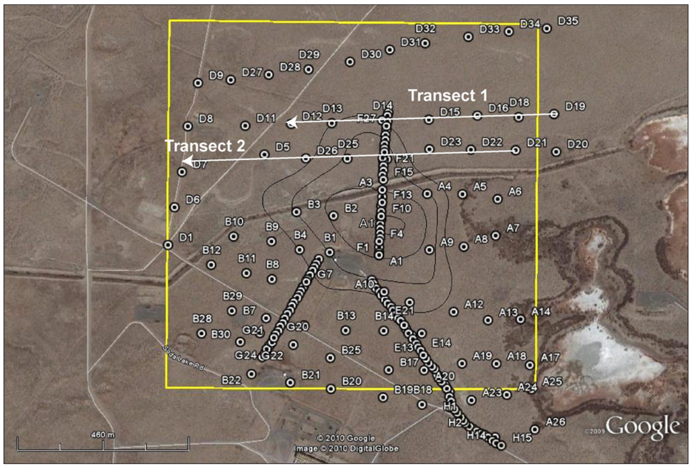

Figure 3. Station location and configuration at Soda Lake. Each station is composed of a high-frequency vertical geophone (4.5 Hz) and a Reftek RT-125 "Texan" digitizer. Contours show subsidence from InSAR analysis of satellite data, with their center considered to be placed above the steam cap (courtesy of Gary Oppliger). The power plant is visible south of study area.

diameter 4 to 5 times larger than that of the outer InSAR contour shown in Figure 3.

The placement of the Imageair Inc. and UNR seismic survey was targeted to cover the steam cap, to the extent the local landscape and infrastructure permitted. The 1.3 km^2, 100 m spaced high - frequency vertical geophone survey, conducted in March 2010, recorded ambient seismic noise (and available earthquake waveforms) for 3 days. A total of four 12 m-separation seismic lines (named "the 12-m seismic lines") were also deployed (Figure 3). We envision this type of seismic survey as preliminary to, or replacing more expensive active experiments, since is aimed to resolving lateral seismic parameter variations at a resolution of approximately 100 m. Also, through successful analysis of the 12 m seismic lines, it may be possible to detect buried faults.

Our technique is based on seismic interferometry (Draganov et al., 2009; Shapiro et al., 2005, Tibuleac et al., 2009), a new imaging method used to generate subsurface images without larger seismic sources such as explosions and earthquakes. One application of seismic interferometry is to retrieve the impulse response or Green's Function (GF) from crosscorrelation of ambient seismic noise. The ambient-noise autocorrelation at each station is interpreted as the collocated source–receiver elastic wave Green's Function (i.e. the Earth's reflection response).

The method includes four steps, as follows: 1) Analysis of fundamental mode Rayleigh waves from Green's Functions (GFs) extracted from ambient seismic noise cross correlation stacks; 2) Analysis of the GF P-reflection component extracted from ambient-noise autocorrelations; 3) Analysis of the geothermal field characteristics in terms of seismic scattering and ambient-noise spectral content; 4) Application of cross and auto correlation analysis to ambient noise data recorded at pairs of sensors on the 12-m seismic lines to generate virtual shot gathers. In this paper we report encouraging results development of Steps 1 and 2.

Results

1) Analysis of fundamental mode Rayleigh waves from Green's Functions (GFs) extracted from ambient seismic noise cross correlation stacks.

By applying cross correlation to ambient noise data recorded at pairs of sensors (A,B, and D stations in Figure 3), deployed at Soda Lake, and stacking the results over a period of time, we generated inter-station GF's, with Rayleigh waves as dominant arrivals. Examples of inter-station GF's obtained on Transects 1 (600 m length) and 2 (shown as white lines in Figure 3) are shown in Figures 4 and 5. Transect 1 includes inter-station paths outside the anomaly (we name "the anomaly" the region centered on station A1 and shown with InSAR contours in Figure 3). Transect 2 (of 800 m length) crosses the northern part of the anomaly. A preliminary estimation of the velocity of phases which we interpret as fundamental Rayleigh waves shows lower surface wave velocity on Transect 2 at frequencies of 1-5 Hz. We also note more scattering (complex GF's) at stations on Transect 2.

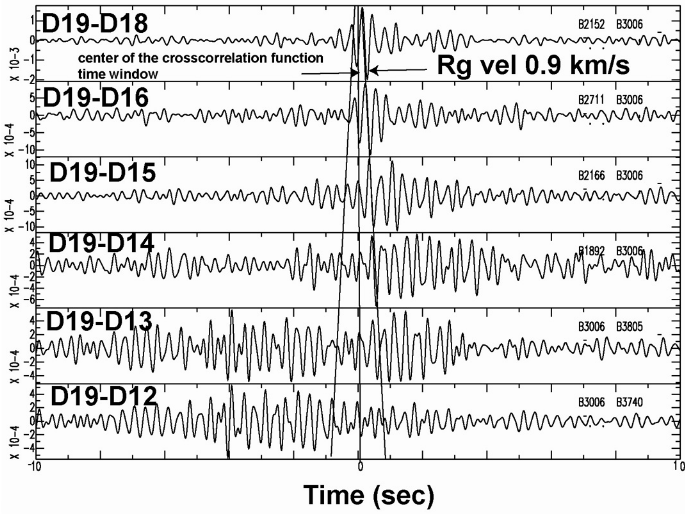

Figure 4. Crosscorrelation stacks for Transect 1 (Figure 1) showing the GF's extracted from D19 waveform crosscorrelations with data recorded at stations D12-D18. The arrival times corresponding to 0.9 km/s velocity are shown on a line, for arrivals interpreted as fundamental Rayleigh waves. The time lag zero corresponds to the center of the crosscorrelation window. In the ideal case, of isotropic ambient noise, the GF's would be symmetrical relative to the center of the crosscorrelation window, with identical causal and a-causal components. In this case, the GF's are identified only on one side of the crosscorrelation function.

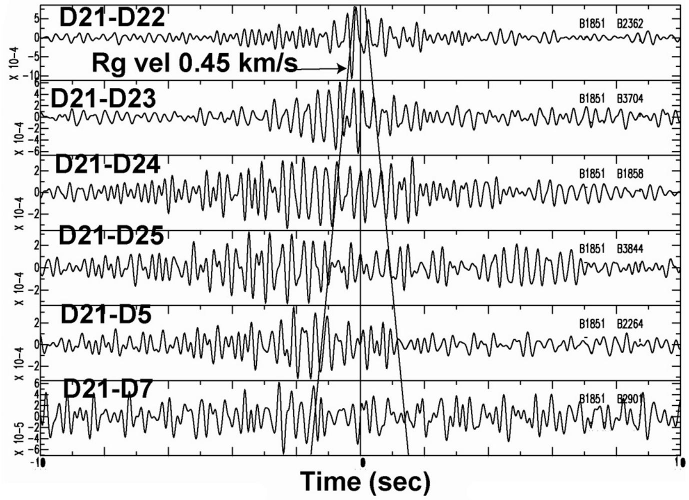

Figure 5. Crosscorrelation stacks for Transect 2 (Figure 1) showing the GF's extracted from D21 waveform crosscorrelations with data recorded at stations D22-D25, D5 and D7. The arrival times corresponding to 0.47 km/s velocity are shown on a line, for arrivals interpreted as fundamental Rayleigh waves. The time lag 0 corresponds to the center of the crosscorrelation window. Like in Figure 2, the GF's are identified only on one side of the crosscorrelation function.

The next step is to use array processing techniques, such as *fk* analysis (frequency-wavenumber) (Tibuleac *et al*, 2009), to estimate Rayleigh - wave phase velocity dispersion curves for ad-hoc sub-arrays of stations. We will invert the dispersion estimates for surface wave velocity models using the Computer Programs in Seismology (CPS3.0) *surf96* algorithm (Herrmann and Ammon, 2002).

2) Analysis of the GF P-reflection component extracted from ambient-noise autocorrelations.

By applying auto-correlation to ambient noise data recorded at individual sensors we retrieve the earth's reflection response at the location of each sensor. Autocorrelation stacks over three

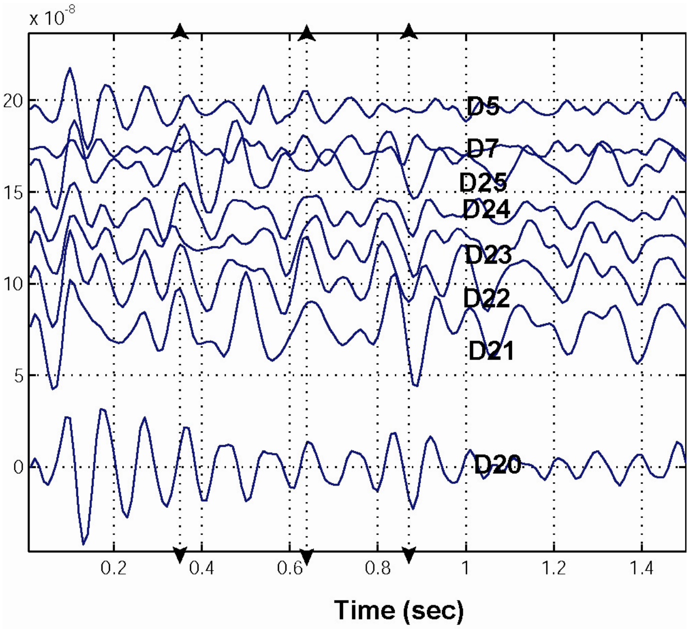

Figure 6. Ambient - noise autocorrelation stacks (weighted) at stations on Transect 2, in a 1.5 sec window. The stations on top of the anomaly (D25-D21) have common arrivals (marked by vertical lines) at ~0.35s, ~ 0.65s, and large arrivals are observed at ~0.85 sec at stations to the NE of the anomaly. Data from more stations is necessary to confirm these arrivals, which we interpret as reflections from subsurface layers. The raw waveforms are processed using automatic gain control in a 0.5 sec window.

days, from stations on Transect 2 in Figure 1 are shown in Figure 6. The autocorrelation traces will be interpreted in terms of reflection GF phase composition, crustal structure, crust-mantle boundary depth, and crustal reflector properties, using waveform modeling programs available at UNR, such as CPS3.0 or e3D (Larsen, 1996).

3) Analysis of the geothermal field characteristics in terms of seismic scattering and ambient-noise spectral content.

Microtremor spectral anomalies in the range of 1-6 Hz have been associated with “partially saturated” hydrocarbon reservoirs (Saenger et al., 2009; Schechinger et al., 2009). Variations in the seismic noise spectral content in the reservoir area have been reported in geothermal areas (Georgsson et al., 2000). These observations suggest that differences between geothermal reservoirs and non-productive areas could be assessed by measuring seismic scattering. We will research possible geothermal reservoir indicators related to seismic scattering, such as: a) the stochastic parameters, such as Hurst number and characteristic length (Pullammanappallil et al., 1997) of the ambient noise autocorrelations and crosscorrelations; b) ambient noise spectral energy differences above the geothermal reservoir, compared with spectral energy measured at positions away from a reservoir for frequency intervals such as 1-3.5 Hz or 1-6 Hz.

4) Application of cross and auto correlation analysis to ambient noise data recorded at pairs of sensors on the 12-m seismic lines to generate virtual shot gathers.

By applying cross-correlation to ambient noise data recorded at pairs of sensors on 12-m seismic lines we will generate virtual shot gathers as if one of the sensors is generating seismic waves, i.e. we will retrieve the earth’s reflection response (Draganov et al., 2009). Using only autocorrelation stacks, preliminary results of two recently deployed co-located surveys near Reno: a passive geophone survey, recording ambient noise and an active source geophone survey have shown similar reflectors, at least to 300 m depth, for sensors located 15 m apart (Tibuleac et al., 2010). The sensors in the geophone lines in Figure 3 were located 12 m apart.

Summary

We develop a method designed to resolving lateral seismic parameter variations at a resolution of approximately 100 m, to be applied prior to, or in replacement of more expensive active experiments. Promising results are obtained from analysis of three days of ambient noise recorded at a 1.3 km^2, 100 m spaced high - frequency vertical geophone survey over a steam cap. A preliminary estimation of the velocity of phases which we interpret as fundamental Rayleigh waves shows lower surface wave velocity and higher scattering within the geothermal production field, at frequencies from 1 to 5 Hz.

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