WS11 C01

Cost-effective Seismic Reflection Imaging Using Seismic Interferometry for Imaging of Enhanced Geothermal System - A Case Study in the Neuquén Basin

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SUMMARY

We investigate the applicability of passive seismic interferometry using P-wave coda from local earthquakes for the purpose of retrieving reflections for imaging enhanced geothermal systems. For this, we use ambient-noise data recorded in the Neuquén basin, Argentina, where the Peteroa and Los Molles geothermal fields are present nearby. After retrieving reflections, we proceed to process them following a standard processing sequence to obtain images of the crustal structures. Examining crosscorrelation, crosscoherence, and multidimensional deconvolution approaches, we find that multidimensional deconvolution, based on the truncated singular-value decomposition scheme, gives us slightly better structural imaging than the other two approaches. Our results provide higher-resolution imaging of the crustal structures down to the lower boundary of the Moho in comparison with previous passive seismic imaging by receiver function and global-phase seismic interferometry in this region. We also interpret the deep basement thrust fault that has been indicated by active-seismic reflection profile and nearby exploration well. The method we propose could be used as a low-cost alternative to active-source acquisition for imaging and monitoring purposes of deeper geothermal reservoirs, e.g., in enhanced geothermal systems, where the target structures are down to 10 km depth.

Introduction

An enhanced geothermal system (or hot dry rock) is a renewable-energy source whose target reservoirs can be as deep as 10 km. In connection with such reservoirs, estimating the Moho depth and the location of major faults is crucial to comprehend the heat flow. Seismic reflection surveys have the potential to provide such imaging information. However, obtaining such deep reflections by active-source seismics (e.g., vibroseis) would be still subject to difficulties (e.g., due to the limited frequency bandwidth, operation costs and possible damage to the environment).

An alternative seismic reflection approach is seismic interferometry (SI). SI provides virtual reflection imaging of the subsurface. Here, we propose to apply SI to local-earthquake P-wave coda (LEPC). Since LEPC SI uses passive sources with a bandwidth confined to the lower frequencies relatively to the active sources, deeper images can be obtained free of shooting cost. In this case study, we retrieve deeper reflections (two-way traveltime ≤ 20 s) using P-wave coda recorded in the Neuquén basin, Argentina (Fig.1), with an exploration-type receiver array called MalARRgue (Ruigrok *et al*. 2012). The Neuquén basin has been producing half of Argentine's domestic hydrocarbons and providing geothermal energy. The Peteroa and Los Molles geothermal projects are in the region of the array (Fig.1).

In the following, we investigate the applicability of LEPC SI by comparing different interferometric theories: crosscorrelation, crosscoherence, and multidimensional deconvolution (MDD).

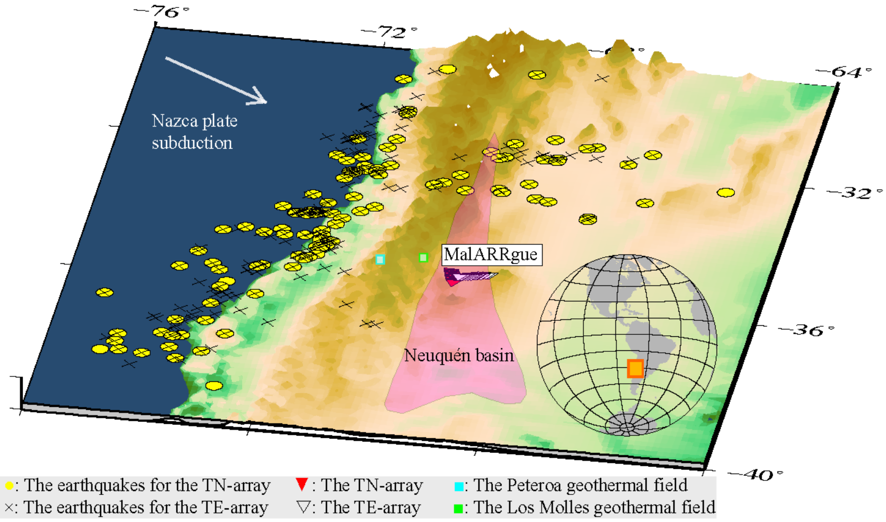

Figure 1 *Topography of TN- and TE-array east of Malargüe, Argentina, with a distribution of local earthquakes recorded by MalARRgue. The pink polygon denotes the location of the Neuquén basin.*

Method

Our assumptions in LEPC SI are:

- P-wave coda contains the scattered waves (thus noise) that are recorded between the direct *P*- and *S*-phase. The coda is extracted by time gating with a time window designed to start after the direct *P*-phase onset and finish before the direct *S*-phase onset.
- Spatial coverage of the earthquakes' epicentres used to extract the P-wave coda is sufficient to effectively suppress retrieval of spurious arrivals in the SI result.

Following Wapenaar (2004), in 3D acoustic medium an equation for LEPC SI by crosscorrelation can be written in frequency domain as

$$2\Re\left\{G^{v,t}_{z,z}(\mathbf{x}_A,\mathbf{x}_B,\omega)\right\}\bar{E}(\omega)\propto-\sum_{S=1}^{n}\left[\left\{V^{c}_{z}(\mathbf{x}_A,\omega)\right\}^{*}\left\{V^{c}_{z}(\mathbf{x}_B,\omega)\right\}\right], \quad (1)$$

where ω denotes frequency, $G_{z,z}^{v,t}(\mathbf{x}_A,\mathbf{x}_B,\omega)$ is the retrieved Green's function, representing particle-velocity measurement (v) recorded by a vertical-component (z) receiver at $\mathbf{x}_A$ due to a traction source (t) at $\mathbf{x}_B$, and $\bar{E}$ is the averaged source-time function over the earthquakes. $v_z^c(\mathbf{x}_A,\omega)$ and $v_z^c(\mathbf{x}_B,\omega)$ are P-wave coda observed from the *n*-th earthquake at $\mathbf{x}_A$ and $\mathbf{x}_B$, respectively.

The relation for SI by crosscoherence is obtained by normalizing the codas in the right-hand side of equation (1) with their amplitude spectra in a stabilized way. Because of this, the averaged source-time function in the left-hand side of equation (1) disappears.

While crosscorrelation and crosscoherence retrieve the scattered Green's function (reflection response) trace by trace, MDD retrieves the Green's function at all receiver positions simultaneously by matrix inversion. For our purposes, we approximate the MDD relation in Wapenaar *et al*. (2011) as

$$\sum_{S=1}^{n}\left\{v_z^c(\mathbf{x}_A,\omega)\right\}^* v_z^c(\mathbf{x}_B,\omega) - \Gamma'(\mathbf{x}_B,\mathbf{x}_A,\omega) \propto \iint_{\partial D_0} G_{z,z}^{scatt,d}(\mathbf{x}_B,\mathbf{x},\omega)\Gamma'(\mathbf{x},\mathbf{x}_A,\omega)d^2\mathbf{x}, \quad (2)$$

where Γ' is the approximated point-spread function that can be extracted from the crosscorrelation result in the right-hand side of equation (1), while $G_{z,z}^{scatt,d}$ is the desired scattered Green's function due to a dipole source. The integral in equation (2) is taken along the receiver positions (earth's surface δD_0). To obtain $G_{z,z}^{scatt,d}$, we perform matrix inversion.

In this study, we investigate two different schemes to stabilize the matrix inversion for MDD: the damped least-squares scheme and the truncated singular-value decomposition (SVD) scheme. While the former is the conventional approach, the latter is the approach recently introduced by Minato *et al.* (2013). The truncated SVD scheme uses an idea related to the sub-space method in machine learning.

A conceptual diagram of LEPC SI is given in Fig.2 while Fig.3 shows the general seismic data-processing flow we apply.

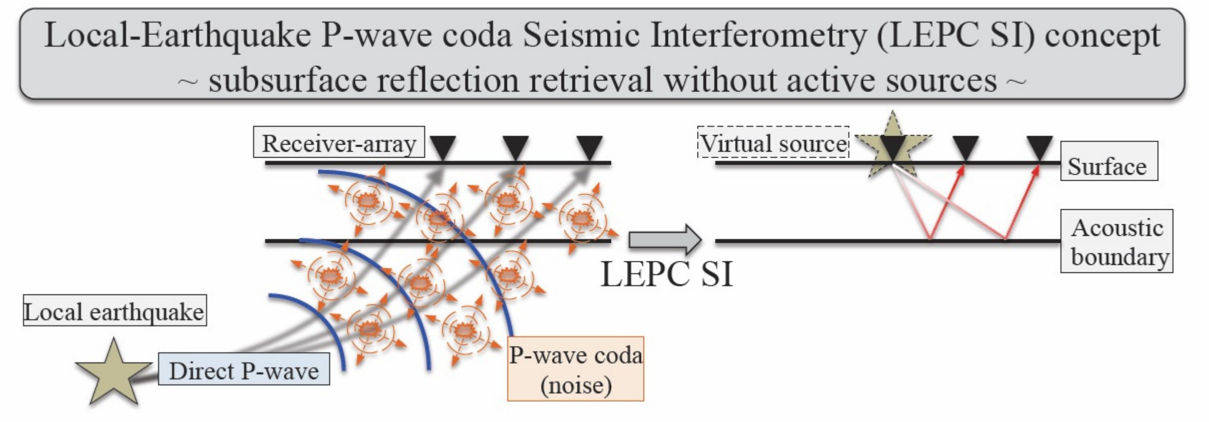

Figure 2 *LEPC SI concept to turn the P-wave coda into reflection signal.*

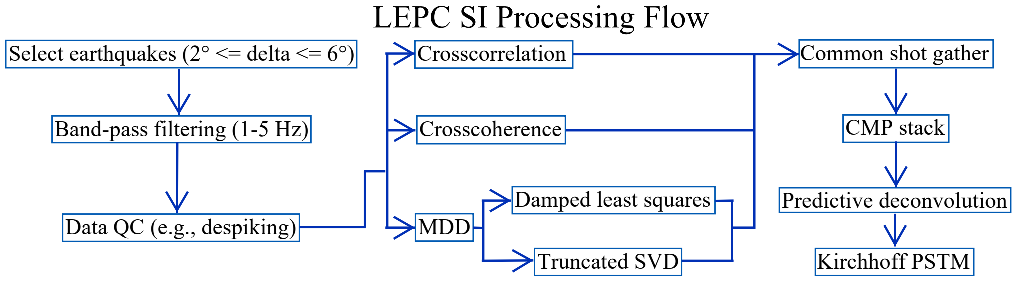

Figure 3 *Seismic processing flow in this study.*

Results and Discussions

Fig. 4 shows examples of retrieved common midpoint (CMP) gathers obtained from LEPC SI by crosscorrelation with velocity semblance plots. In these plots, some degree of correspondence can be observed between the semblance peaks and a regional velocity model (Farías *et al*. 2010).

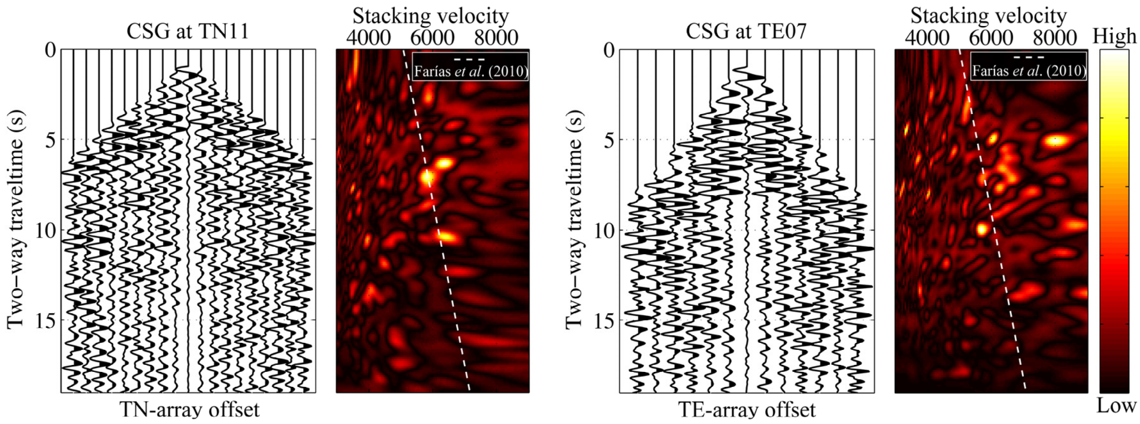

Figure 4 *CMP gathers with velocity. Stations TN11 and TE07 are located in the middle of the TN- and TE-arrays, respectively. The white dashed lines indicate the regional velocity model (Farías et al., 2010).*

Fig.5 shows the resulting CMP stacks from LEPC SI by crosscorrelation.

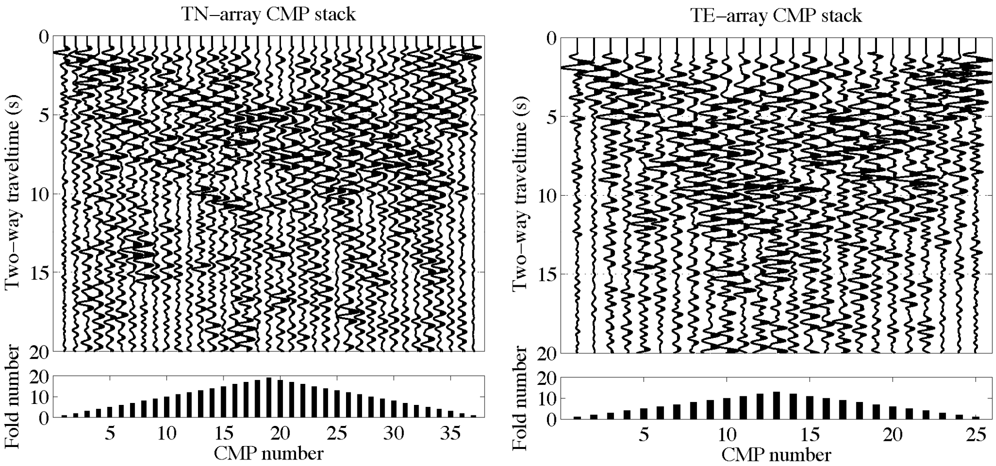

Figure 5 *CMP stack along the TN- and TE-array.*

After applying predictive deconvolution for possible multiples caused by the top of basement (bottom of the basin), we migrate the processed data to correct for dipping structure using a Kirchhoff algorithm. Comparisons of LEPC SI migrated imaged from the three different SI approaches are shown in Fig. 6. The damped least-squares MDD scheme give less stable results with our field dataset, so we show only the results of the truncated SVD scheme.

Gilbert *et al*. (2006) used receiver functions to reveal a bifurcated Moho at a depth of 35 km (around 10-12 s in Fig. 6). Nishitsuji *et al*. (2016) confirmed such Moho structures by global-phase seismic interferometry (the blue dotted lines in Fig. 6). Moreover, according to the nearby exploration well (LPis x-1), deep basement thrust faults are expected to be beneath the TE-array. Such fault feature (the green line in Fig. 6) is more interpretable in the MDD result than in the other results in Fig. 6. Thus, we find that the MDD result provides better structural-interpretation possibilities in this study.

Based on the obtained MDD image, we think that LEPC SI, together with resistivity investigations, might be useful for enhanced geothermal-systems characterization.

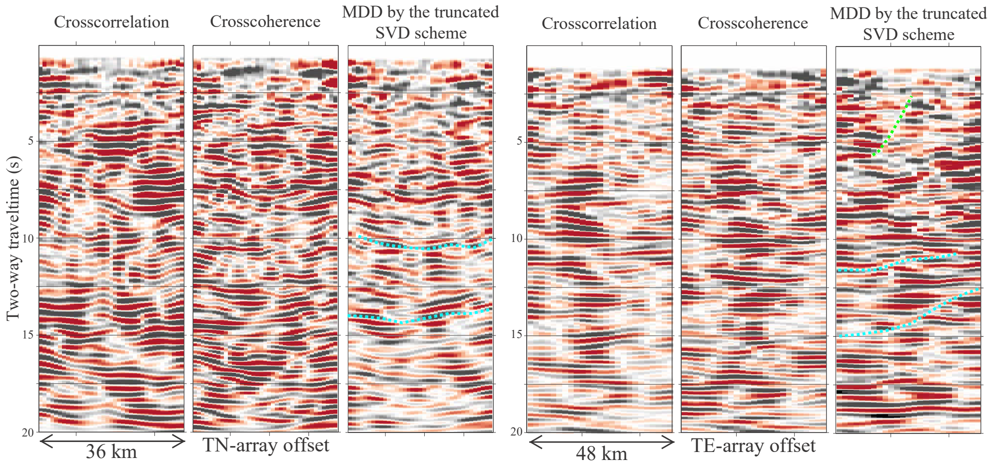

Figure 6 *Comparison of LEPC SI images from crosscorrelation, crosscoherence, and MDD. The blue lines indicate the Moho interpreted by Gilbert et al. (2006) and Nishitsuji et al. (2016). The green line indicates a major deep basement thrust fault by the exploration well (LPis x-1).*

Conclusions

We showed a seismic-interferometry method that uses P-wave coda of local earthquakes (2° ≤ epicentral distance ≤ 6°) for body-wave retrievals in order to image subsurface structures. We used field data recorded at a part of the Neuquén basin, Argentina. The results retrieved using multidimensional deconvolution with a singular-value decomposition scheme allowed interpretation of the Moho and a major deep basement thrust fault. This suggests that our method has a possible application for crustal-scale imaging for, e.g., deep geothermal explorations.

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References

Farías, M. *et al*. [2010] Crustal-scale structural architecture in central Chile based on seismicity and surface geology: Implications for Andean mountain building. *Tectonics*, **29**, TC3006.

Gilbert, H., Beck, S. and Zandt, G. [2006] Lithospheric and upper mantle structure of central Chile and Argentina. *Geophysical Journal International*, **165**, 383-398.

Minato, S., Matsuoka, T. and Tsuji, T. [2013] Singular-value decomposition analysis of source illumination in seismic interferometry by multidimensional deconvolution. *Geophysics*, **78**, Q25-Q34.

Nishitsuji, Y., Ruigrok, E., Gomez, M., Wapennar, K. and Draganov, D. [2016] Reflection imaging of aseismic zones of the Nazca slab by Global-phase seismic interferometry. Submitted to *Interpretation*.

Ruigrok, E., Draganov, D., Gomez, M., Ruzzante, J., Torres, D., Lopes Pumarega, I., Barbero, N., Ramires, A., Castano Ganan, A. R., van Wijk, K., and Wapenaar, K. [2012] Malargüe seismic array: Design and deployment of the temporary array. *The European Physical Journal Plus*, **127**, 126.

Wapenaar, K. [2004] Retrieving the elastodynamic Green's function of an arbitrary inhomogeneous medium by cross correlation. *Physical Review Letters*, **93**, 254301.