

## Crustal-scale reflection imaging and interpretation by passive seismic interferometry using local earthquakes

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## 22 **Abstract**

23 We show application of passive seismic interferometry (SI) using P-wave coda of local  
24 earthquakes for the purpose of crustal-scale reflection imaging. We process the reflec-  
25 tion gathers retrieved from SI following a standard seismic processing in exploration  
26 seismology. We apply SI to the P-wave coda using crosscorrelation, crosscoherence, and  
27 multidimensional deconvolution approaches for data recorded in the Malargüe region,  
28 Argentina. Comparing the results from the three approaches, we find that multidimen-  
29 sional deconvolution based on the truncated singular-value decomposition scheme gives  
30 us a substantially better structural imaging. Although our results provide higher reso-  
31 lution images of the subsurface, it shows less clear images for the Moho in comparison  
32 with previous seismic images in the region obtained by receiver function and global-  
33 phase seismic interferometry. Above the Moho, though, , we interpret a deep thrust  
34 fault and the possible melting zones which are previously indicated by active-seismic  
35 and magnetotelluric methods in this region, respectively. The method we propose could  
36 be an alternative option not only for crustal-scale imaging, e.g., in enhanced geothermal  
37 systems, but also for the lithospheric-scale as well as basin-scale imaging, depending on  
38 the availability of local earthquakes and the frequency bandwidth of their P-wave coda.

## 39 **Introduction**

40 Crustal imaging is vitally relevant for understanding processes like earthquake mecha-  
41 nisms, magmatism, deep geothermal explorations, and basin tectonics. In order to ob-  
42 tain an image of the crust, both active sources (e.g., vibroseis and airguns) and passive  
43 sources (e.g., ambient noise and earthquakes) have been used. For the former, the reflec-  
44 tion method (e.g., Granath et al., 2010) and refraction method (e.g., Zhao et al., 2013)  
45 are well known, whereas for the latter, travelttime tomography (Aki et al., 1977), full  
46 waveform tomography (Operto et al., 2006), receiver function (Langston, 1979), and the

47 Sp-waves method (Doi and Kawakata, 2013) have been applied.

48 A very attractive passive seismic method is seismic interferometry (SI) (e.g., Aki,  
49 1957; Claerbout, 1968; Campillo and Paul, 2003; Shapiro and Campillo, 2004; Wape-  
50 naar, 2004), which retrieves virtual seismic records from existing seismic records. In  
51 this study, we focus on body-wave SI. Although the imaging resolution achieved by  
52 passive SI might not be easily compatible with the one achieved by the active-source  
53 reflection method, it has a potential to contain low-frequency information, i.e.,  $\leq 5$  Hz,  
54 which enables us to interpret deeper structures, such as in the lower crust and lithosphere.  
55 Moreover, as an economically attractive aspect, the shooting cost of the passive seismic  
56 method is zero. For reflection retrieval by passive SI, several applications have been  
57 already reported, both for ambient noise (e.g., Draganov et al., 2009; Zhan et al., 2010;  
58 Ryberg, 2011; Panea et al., 2014; Almagro Vidal et al., 2014) and local earthquakes (e.g.,  
59 Nakata et al., 2011, 2014).

60 There are five ways SI can be applied: using correlation (Claerbout, 1968; Duvall et  
61 al., 1993); coherence (Aki, 1957); trace deconvolution (Snieder and Şafak, 2006; Vas-  
62 concelos and Snieder, 2008a, 2008b); convolution (Slob et al., 2007); and multidimen-  
63 sional deconvolution (MDD; Wapenaar et al., 2008). Nakata et al. (2011) compared the  
64 common midpoint (CMP) stacks obtained from SI by crosscorrelation, trace deconvolu-  
65 tion, and crosscoherence using traffic noise. The authors suggested that the selection of  
66 a proper SI method depends on the data set at hand. In addition to the synthetic compar-  
67 ison of the results obtained from crosscorrelation and MDD by Wapenaar et al. (2011),  
68 Nakata et al. (2014) compared SI results obtained using trace deconvolution, cross-  
69 coherence, and MDD results (after applying wavefield decomposition), applied to data  
70 representing local earthquakes in order to retrieve reflected plane waves. They concluded  
71 that MDD provides gathers that have the best signal-to-noise ratio among the compared  
72 SI methods.

73 In this paper, we propose a seismic imaging technique that applies passive SI (two-

74 way traveltimes  $\leq 20$  s) to P-wave coda due to local earthquakes ( $2^\circ \leq$  epicentral distances  
75  $\leq 6^\circ$ ). Hereafter, we abbreviate this method as LEPC (local-earthquake P-wave coda)  
76 SI. The coda waves are the tail part of a signal consisting of multiply scattered waves  
77 (Snieder, 2004). Hence, we assume that their directivity is weak (e.g., Mayeda et al.,  
78 2007; Baltay et al., 2010; Abercrombie, 2013), and thus that they illuminate the subsur-  
79 face beneath the receivers favorably for retrieval of reflections. We apply LEPC SI to  
80 data recorded by an exploration-type receiver array called MalARRgue (Ruigrok et al.,  
81 2012) that was located in the Malargüe region (Mendoza, Argentina) (Figure 1). Because  
82 the west coast of Chile has considerable seismicity due to the Nazca-slab subduction, we  
83 choose this region to test LEPC SI.

84 In the following, we show how to apply LEPC SI using the different retrieval methods  
85 (crosscorrelation, crosscoherence, and MDD) for the purpose of crustal-scale reflection  
86 imaging.

## 87 **Study Area and Data**

88 The Malargüe region is located in the northern part of the Neuquén basin, Argentina.  
89 This basin has been producing nearly half of the Argentine hydrocarbons, but has also  
90 been providing geothermal power. The Peteroa Volcano, which is an active volcano in  
91 the Andes Mountains in the Malargüe region, is situated close to part of the array we use  
92 (Figure 1). The locations of local earthquakes that occurred in 2012 around the Malargüe  
93 region are shown in Figure 1 on a topography map (Becker et al., 2009). The source  
94 locations of the earthquakes are provided by Java version of Windows Extracted from  
95 Event Data (JWEED) operated by the Incorporated Research Institutions for Seismology  
96 (IRIS). We define local earthquakes as those earthquakes whose epicentral distances are  
97 between  $2^\circ$  and  $6^\circ$ . This definition is close to the one introduced by Kayal (2008). For  
98 the sake of terminological clarification, regional earthquakes, which we do not use in  
99 this study, are the earthquakes whose epicentral distances are larger than  $6^\circ$ . In Figure

1, we indicate with triangles the location of the part of the MalARRgue that we use in our study: the T-array, which is an linear receiver array deployed at the surface. The T-array consists of two linear subarrays: the TN-array with 19 stations spaced every 2 km (labeled TN02 to TN20; white triangles in Figure 1), oriented in the NNW direction; the TE-array with 13 stations spaced every 4 km (labeled TE01 to TE13; black triangles in Figure 1), oriented in the ENE direction. These stations are three-component velocity sensors. The 115 circles and 210 stars indicate the location of the local earthquakes recorded by the TN- and TE-array, respectively, and characterized by sufficient signal-to-noise-ratio of the P-wave coda. The TE-array recorded a higher number of earthquakes than the TN-array, because the TE-array was operating longer. The coverage of back azimuth of these earthquakes with respect to the T-array is wide (see Figures 1 and 2). A complete list of the local earthquakes used in this study is shown in Table 1.

## Local-Earthquake P-wave Coda Seismic Interferometry (LEPC SI)

### Crosscorrelation

In Claerbout (1968), virtual reflection traces were retrieved from the autocorrelation of the recorded transmission response in a horizontally layered medium. Later, he conjectured that in 3D inhomogeneous media, one has to use crosscorrelation to retrieve the reflection response between two receivers at the surface. This was proven by Wapenaar (2004) for an arbitrary inhomogeneous elastic medium. The author showed that the Green's function  $G_{p,q}^{v,t}(\mathbf{x}_A, \mathbf{x}_B, \omega)$ , representing particle-velocity measurement ( $v$ ) in the  $p$ -direction at a receiver at  $\mathbf{x}_A$  due to a point single-force ( $t$ ) at  $\mathbf{x}_B$  in the  $q$ -direction, can be retrieved from the crosscorrelation of observed particle-velocity measurements  $v_p^{obs}$  and  $v_q^{obs}$  at  $\mathbf{x}_A$  and  $\mathbf{x}_B$ , respectively, from uncorrelated noise sources in the subsurface:

$$2\text{Re}\{G_{p,q}^{v,t}(\mathbf{x}_A, \mathbf{x}_B, \boldsymbol{\omega})\}S_N(\boldsymbol{\omega}) \approx -\left\langle \left\{ v_p^{obs}(\mathbf{x}_A, \boldsymbol{\omega}) \right\}^* \left\{ v_q^{obs}(\mathbf{x}_B, \boldsymbol{\omega}) \right\} \right\rangle. \quad (1)$$

124 The above equation is written in the frequency domain, indicated by the angular fre-  
 125 quency  $\boldsymbol{\omega}$ ; the asterisk denotes complex conjugation;  $\langle \rangle$  indicates averaging over source  
 126 realizations; and the particle-velocity measurements are in the  $p$ - and  $q$ -directions. The  
 127 observed data  $v^{obs}$  is representing the superposition of recordings from uncorrelated  
 128 noise sources distributed along a surface that illuminated the received from all directions.  
 129  $S_N(\boldsymbol{\omega})$  denotes the power spectrum of the noise. Due to the source-receiver configuration  
 130 in this study, we exclude the direct wave, which would not fall inside the stationary-phase  
 131 region for retrieval of reflections. This happens because the epicentral distances of the  
 132 earthquakes are relatively long compared to their hypocentral depth. We thus aim to use  
 133 arrivals characterized by slowness smaller than the ones characterizing the direct waves.  
 134 Note that the exclusion of the direct waves might give rise to artifacts in the retrieved  
 135 response. Nevertheless, these artifacts should not pose a problem as long as our main  
 136 aim is to recover the primary reflections. Moreover, having sufficiently long record-  
 137 ings of coda waves would ensure illumination of the receivers from all directions due to  
 138 equipartitioning. In such a case, one can exchange the noise recordings in equation (1)  
 139 by recordings of coda waves  $v^c$ . For our application, we define an observed P-wave coda  
 140 of a local earthquake as

$$v_z^c(\mathbf{x}_A, \boldsymbol{\omega}) = G_z^c(\mathbf{x}_A, \mathbf{x}_S, \boldsymbol{\omega})E(\mathbf{x}_S, \boldsymbol{\omega}), \quad (2)$$

141 where  $z$  indicates that we are using the vertical component of the recordings and  $E(\mathbf{x}_S, \boldsymbol{\omega})$   
 142 is the Fourier transform of the source time function (STF) of a local earthquake at  $\mathbf{x}_S$  in  
 143 the subsurface. As P-wave coda, we use the part of the recording after the direct arrival

144 of the  $P$ -phase and before the direct arrival of the  $S$ -phase.

145 Because of the limitation on the length of the coda recordings, we cannot expect that  
 146 the receivers would be illuminated equally well from all directions. Because of this, we  
 147 would like to repeat the correlation for many local earthquakes with wide distribution of  
 148 the back azimuth (see Figures 1 and 2) and to average the separate correlations. Thus we  
 149 rewrite equation (1) as

$$2Re \{G_{z,z}^{v,t}(\mathbf{x}_A, \mathbf{x}_B, \omega)\} \bar{S}_E(\omega) \propto - \sum_{S=1}^n [\{v_z^c(\mathbf{x}_A, \omega)\}^* v_z^c(\mathbf{x}_B, \omega)], \quad (3)$$

150 where we have exchanged  $\langle \rangle$  of equation (1) by a summation over the independent local  
 151 earthquakes.  $\bar{S}_E(\omega)$  denotes the average power spectrum of the STF over the earth-  
 152 quakes.

### 153 Crosscoherence

154 The crosscoherence method (Aki, 1957) is a technique to normalize the amplitude among  
 155 different source or receiver pairs. By applying SI by crosscoherence instead of crosscor-  
 156 relation we expect to retrieve better signal-to-noise ratio in terms of the phase in com-  
 157 parison with the crosscorrelation (e.g., Prieto et al., 2009; Nakata et al., 2011). To apply  
 158 SI by crosscoherence, we rewrite equation (3) as

$$2Re \{G_{z,z}^{v,t}(\mathbf{x}_A, \mathbf{x}_B, \omega)\} \propto \sum_{S=1}^n \frac{\{v_z^c(\mathbf{x}_A, \omega)\}^* v_z^c(\mathbf{x}_B, \omega)}{|v_z^c(\mathbf{x}_A, \omega)| |v_z^c(\mathbf{x}_B, \omega)| + \varepsilon}, \quad (4)$$

159 where  $\varepsilon$  denotes a stabilization factor (also called a damping factor or a regularization  
 160 parameter). Since the crosscoherence enhances both the signal and the noise, it is im-  
 161 portant to have data that is not dominated by noise. Note that in the above equation, the  
 162 retrieved Green's function is no longer modulated by the average power spectrum of the



163 STF, as the crosscoherence eliminates it.

## 164 **Multidimensional Deconvolution (MDD)**

165 While the aforementioned crosscorrelation and crosscoherence calculate the reflection  
166 response trace by trace, MDD is a receiver-array-based SI method that calculates the  
167 reflection response (the scattered Green's function in Wapenaar et al., 2011) simultane-  
168 ously for all observed responses via matrix inversion. Although the application of MDD  
169 requires regularly-spaced receivers, a point-spread function (PSF), and a regularization  
170 approach for the matrix inversion, this technique theoretically removes the influence of  
171 the (variation of the) STF of the sources, takes intrinsic attenuation into account (which is  
172 not the case for correlation nor coherence) and compensates for possibly inhomogeneous  
173 illumination of the receivers by the coda wavefield.

174 The PSF is a well-known gauge for imaging quality in optics, such as microscopy. In  
175 exploration seismology, the PSF is used to quantify the effect of the source and receiver  
176 distribution and of the STF on the imaging results. In analogy with this, van der Neut  
177 et al. (2010, 2011) showed that the result from SI by crosscorrelation could actually be  
178 seen as the blurring (temporal and spatial convolution) of the desired scattered Green's  
179 function with a PSF. This PSF is obtained from the crosscorrelation of recordings at the  
180 receivers at the surface as if above the receivers there were a homogeneous half space  
181 (e.g., Wapenaar et al., 2011). Nakahara and Haney (2015) recently showed that the  
182 PSF could also be used for studying earthquake sources. Application of SI by MDD  
183 is actually deconvolving the crosscorrelation result by the PSF. To obtain the required  
184 wavefield for the retrieval of the correlation result and the PSF, one can apply wavefield  
185 decomposition at the Earth's surface (Nakata et al., 2014). This, though, would require  
186 a good velocity model for the near surface, which in areas like Malargüe, characterized  
187 by strong lateral inhomogeneity, is not readily available. Because it is not possible to  
188 obtain measurements as if the Earth's surface were covered by a homogeneous half space,

189 following Wapenaar et al. (2011) we use an approximate relation for the application of  
 190 SI by MDD:

$$\sum_{S=1}^n [\{v_z^c(\mathbf{x}_A, \omega)\}^* v_z^c(\mathbf{x}_B, \omega)] - 2\Gamma(\mathbf{x}_B, \mathbf{x}_A, \omega) \propto \iint_{\partial D_0} G_{z,z}^{scatt,d}(\mathbf{x}_B, \mathbf{x}, \omega) \Gamma(\mathbf{x}, \mathbf{x}_A, \omega) d^2 \mathbf{x} \quad (5)$$

191 where  $\Gamma$  is the approximated PSF and  $G_{z,z}^{scatt,d}$  is the scattered Green's function due to  
 192 a dipole source. Figure 3 shows a schematic image of the terms in equation (5). The  
 193 integral in equation (5) is taken along the receiver positions (Earth's surface  $\partial D_0$ ). A  
 194 derivation of equation (5) is given in Appendix A. Just like Wapenaar et al. (2011),  
 195 we look at the recorded wavefield as a part that will be recorded at the receivers in the  
 196 absence of a free surface and a part due to the presence of the free surface (which is  
 197 the former after being reflected at the free surface at least once). The  $\Gamma$  in equation (5)  
 198 (see Figures 9c and 9f later in this paper) can be estimated by extracting time-windowed  
 199 signals from the crosscorrelation at  $\mathbf{x}_A$  and  $\mathbf{x}_B$  (the right-hand side of equation 3) (see  
 200 Figures 9c and 9f later in this paper) of the wavefield that would be recorded in the  
 201 absence of a free surface at the receivers. The signals that make up  $\Gamma$  exhibit a butterfly-  
 202 shaped window around  $t = 0$  (see Figures 9c and 9f later in this paper), narrowest when  
 203  $\mathbf{x}_A = \mathbf{x}_B$ . We assume that the contribution from the crosscorrelation at  $\mathbf{x}_A$  and  $\mathbf{x}_B$  of the  
 204 wavefield that would be recorded due to the presence of a free surface at the receivers is  
 205 sufficiently small to be neglected (van der Neut et al., 2010; Wapenaar et al., 2011). Note  
 206 that the numerical test showed that the approximation can provide the correct scattered  
 207 Green's function with small inversion artifacts (van der Neut et al., 2010). For notational  
 208 simplicity, we define the left hand-side of equation (5) as

$$C'(\mathbf{x}_B, \mathbf{x}_A, \omega) = \sum_{S=1}^n [\{v_z^c(\mathbf{x}_A, \omega)\}^* v_z^c(\mathbf{x}_B, \omega)] - 2\Gamma(\mathbf{x}_B, \mathbf{x}_A, \omega). \quad (6)$$

209 Substituting equation (6) in equation (5), we obtain

$$C'(\mathbf{x}_B, \mathbf{x}_A, \omega) \propto \iint_{\partial D_0} G_{z,\bar{z}}^{scatt,d}(\mathbf{x}_B, \mathbf{x}, \omega) \Gamma(\mathbf{x}, \mathbf{x}_A, \omega) d^2\mathbf{x}. \quad (7)$$

210 Equation (7) can be discretized by fixing the position of  $\mathbf{x}_B$  and varying the receiver

211 position  $\mathbf{x}_A$ :

$$\begin{pmatrix} C'(\mathbf{x}_B, \mathbf{x}_1, \omega) \\ C'(\mathbf{x}_B, \mathbf{x}_2, \omega) \\ \vdots \\ C'(\mathbf{x}_B, \mathbf{x}_m, \omega) \end{pmatrix} \propto \begin{pmatrix} \Gamma(\mathbf{x}_1, \mathbf{x}_1, \omega) & \Gamma(\mathbf{x}_2, \mathbf{x}_1, \omega) & \cdots & \Gamma(\mathbf{x}_m, \mathbf{x}_1, \omega) \\ \Gamma(\mathbf{x}_1, \mathbf{x}_2, \omega) & \Gamma(\mathbf{x}_2, \mathbf{x}_2, \omega) & \cdots & \Gamma(\mathbf{x}_m, \mathbf{x}_2, \omega) \\ \vdots & \vdots & \ddots & \vdots \\ \Gamma(\mathbf{x}_1, \mathbf{x}_m, \omega) & \Gamma(\mathbf{x}_2, \mathbf{x}_m, \omega) & \cdots & \Gamma(\mathbf{x}_m, \mathbf{x}_m, \omega) \end{pmatrix} \begin{pmatrix} G_{z,\bar{z}}^{scatt,d}(\mathbf{x}_B, \mathbf{x}_1, \omega) \\ G_{z,\bar{z}}^{scatt,d}(\mathbf{x}_B, \mathbf{x}_2, \omega) \\ \vdots \\ G_{z,\bar{z}}^{scatt,d}(\mathbf{x}_B, \mathbf{x}_m, \omega) \end{pmatrix}, \quad (8)$$

212 where we assume that we have  $m$  receivers in total. We can simplify equation (8) using

213 matrix-vector notation:

$$\mathbf{c}' \propto \mathbf{\Gamma} \mathbf{g}, \quad (9)$$

214 where  $\mathbf{\Gamma}$  is a  $m \times m$  matrix, respective  $\mathbf{c}'$  and  $\mathbf{g}$  are  $m \times 1$  column vectors showing receiver

215 gathers. Constructing multiple column vectors using equation (8) for variable  $\mathbf{x}_B$  and

216 arranging them as columns of a matrix, we obtain:

$$\mathbf{C}' \propto \mathbf{\Gamma} \mathbf{G}, \quad (10)$$

217 where  $\mathbf{C}'$  and  $\mathbf{G}$  are  $m \times m$  monochromatic matrices containing  $C'(\mathbf{x}_m, \mathbf{x}_m, \omega)$  and  $G_{z,z}^{scatt,d}(\mathbf{x}_m, \mathbf{x}_m, \omega)$ ,  
 218 respectively. Estimating the dipole scattered Green's function in equation (10) requires  
 219 matrix inversion:

$$\mathbf{G}' \propto [\mathbf{\Gamma}]^{-g} \mathbf{C}', \quad (11)$$

220 where  $[\mathbf{\Gamma}]^{-g}$  is a generalized inverse of  $\mathbf{\Gamma}$ , and  $\mathbf{G}'$  is an estimate of  $\mathbf{G}$ .

221 Note that our receiver configuration might not be optimal for MDD studies. The  
 222 number of receivers we have is relatively small - 19 and 13 for the TN- and TE-array,  
 223 respectively. Fewer receivers leads to more severely ill-posed solutions in the inver-  
 224 sion process. Two approaches to stabilize the MDD in equation (11) have been used: a  
 225 damped least-squares (Menke, 1989); and a singular-value decomposition (SVD; Klema  
 226 and Laub, 1980).

### 227 **MDD by Damped Least Squares**

228 The damped least-square solution is a commonly used approach for MDD studies (e.g.,  
 229 Wapenaar et al., 2008; van der Neut et al., 2011; Boullenger et al., 2015). This scheme  
 230 can be directly adapted to the generalized inverse matrix in equation (11), resulting in

$$\mathbf{G}' \approx [\mathbf{\Gamma}^\dagger \mathbf{\Gamma} + \varepsilon \mathbf{I}]^{-1} \mathbf{\Gamma}^\dagger \mathbf{C}', \quad (12)$$

231 where  $\varepsilon$  and  $\mathbf{I}$  indicate a stabilization factor and the identity matrix, respectively. The

232 symbol  $\dagger$  denotes the complex conjugate transpose matrix. In practice,  $\mathbf{\Gamma}$  is estimated in  
 233 the time domain and then transformed to the frequency domain by the Fourier transform.  
 234 A disadvantage of this scheme is that choosing an appropriate stabilization factor tends  
 235 to be inevitably subjective because it is difficult to evaluate the data redundancy in a  
 236 quantitative way.

### 237 **MDD by Truncated Singular-Value Decomposition (SVD)**

238 There are only a few examples of MDD based on the truncated SVD scheme (e.g., Mi-  
 239 nato et al., 2011, 2013). The concept of the truncated SVD scheme is fundamentally  
 240 close to the principal component analysis (Pearson, 1901) in machine learning, which  
 241 is also called a subspace method or Karhunen-Loève expansion, and the latent semantic  
 242 analysis (Borko and Bernick, 1963) in natural language processing. For example, both  
 243 the truncated SVD scheme and the principal component analysis find the data directions  
 244 (axes) from the eigenvectors of the covariance matrix using the SVD algorithm via La-  
 245 grange multiplier. Here, we briefly introduce the truncated SVD scheme.

246 Let us define the SVD of  $\mathbf{\Gamma}$  in equation (10) as:

$$\mathbf{\Gamma} = \mathbf{U} \begin{pmatrix} \mathbf{\Delta}_r & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{pmatrix} \mathbf{V}^\dagger, \quad (13)$$

247 where  $\mathbf{U}$  is a left-singular matrix (orthonormal-basis matrix),  $\mathbf{V}$  is a right-singular ma-  
 248 trix (orthonormal-basis matrix).  $\mathbf{V}^\dagger$  is the adjugate (adjoint) matrix that is the complex  
 249 conjugate transpose matrix of  $\mathbf{V}$ .  $\mathbf{\Delta}_r$  is an  $r \times r$  diagonal matrix whose elements are  
 250 the singular values of the monochromatic matrix  $\mathbf{\Gamma}$ , obtained by truncation. We define  
 251 the dimension  $r$  as the number of significant singular values by specifying a threshold  
 252 value. Then, we adapt the Moore-Penrose pseudoinverse (Golub and van Loan, 1983)  
 253 for equation (13):

$$[\mathbf{\Gamma}]^{-g} = \mathbf{V} \begin{pmatrix} \mathbf{\Delta}_r^{-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{pmatrix} \mathbf{U}^\dagger, \quad (14)$$

254 where  $\mathbf{U}^\dagger$  is the adjugate (adjoint) matrix of  $\mathbf{U}$ . In the following section, we show the  
 255 MDD results of the damped least-squares scheme and the truncated SVD scheme.

## 256 **Data Processing**

### 257 **Preprocessing**

258 Our first step in the preprocessing is to remove the instrument response from the recorded  
 259 data. After that, we compute power spectral densities (PSD) of the local earthquakes to  
 260 determine a frequency band that exhibits adequate signal-to-noise ratio. Examples of  
 261 PSD of the local earthquake for the TE-array are shown in Figure 4. Analyzing the  
 262 PSDs, we choose the frequency band 1-5 Hz for further seismic processing. We set the  
 263 high end of the band at 5 Hz due to the presence of irregular noise around 8 Hz (see  
 264 Figure 4), which is masking the signals from weaker earthquakes. The nature of this  
 265 noise is not clear. The stations are away from continuous anthropogenic sources, so  
 266 this could be excluded as main contributor. Since this noise is almost continuously seen  
 267 over the records in MalARRgue, it might be connected to the wave action in the nearby  
 268 lake Llanquanelo (Figure 1), but possibly also with deeper activity below the volcanic  
 269 cones in the vicinity of the array. The noise, which is also continuously seen around  
 270 0.3 Hz, likewise to be due to the double-frequency microseisms. In principle, one can  
 271 use higher frequency (if available) for LEPC SI to obtain images of shallower structures,  
 272 e.g., at basin scale. For speeding up the computations, after the band-pass filtering, we  
 273 downsample the data to 0.05 s (Nyquist frequency of 10 Hz) from the original sampling  
 274 of 0.01 s (Nyquist frequency of 50 Hz).

275 The useful window length of the coda of the  $P$ -wave phase is explained in Figure 5  
276 as a function of the epicentral distance. To calculate the times in Figure 5, we use the  
277 regional velocity model of Farías et al. (2010) down to 110 km and ak135 (Kennett et  
278 al., 1995) deeper than that. In order to only extract the  $P$ -wave coda without the direct  
279 wave that usually brings strong directivity in the SI results, we refer to the scaling re-  
280 lation between the moment magnitude,  $M_W$ , and the source duration of the earthquakes  
281 (Kanamori and Brodsky, 2004) assuming that  $M_W$  is proportional to  $M_b$  for our magni-  
282 tude range (Atkinson and Boore, 1987). Thus, our coda-waves extraction window starts  
283 at the time obtained from the summation of the time of the expected  $P$ -phase arrival and  
284 the expected time length of the STF.

285 For the local earthquakes ( $2^\circ \leq$  epicentral distances  $\leq 6^\circ$ ), surface waves are ex-  
286 pected to arrive almost simultaneously with the  $S$ -wave phase onset or later (Kennett et  
287 al., 1995). To make sure that the coda does not contain surface waves related to the earth-  
288 quake, our coda-wave extraction window terminates a few seconds before the observed  
289  $S$ -wave phase onset.

290 With the above window-length selection criteria, the coda duration is shorter for some  
291 earthquakes, but still we have sufficient coda duration (e.g., 15-70 s) for the subsurface  
292 imaging. An example of the coda extraction is shown in Figure 6. For subsequent seismic  
293 processing, we use only the  $P$ -wave coda (the blue window) extracted from the vertical  
294 component. It is difficult to estimate how much converted  $S$ -wave phases are present  
295 within the  $P$ -wave coda, but they most probably are present. Especially,  $SV$ -waves are  
296 expected to be present on the vertical component we use. In this study, we assume that  
297 the  $SV$ -waves are not dominantly recorded for deeper earthquakes (e.g., 50-100 km) due  
298 to their small slowness. For shallower earthquakes (e.g., 0-50 km), the  $SV$ -waves can  
299 be recorded with spatial aliasing due to the larger ray parameter compared to the ray  
300 parameter for  $P$ -waves. However, the crosscorrelation and summation process should  
301 suppress such aliasing effects, emphasizing the reflection responses of the structures.

302 Note that the transverse component in Figure 6 is displayed only for the purpose of data  
303 comparison with the vertical component.

304 After extracting the P-wave coda from each selected local earthquake, we interpolate  
305 missing traces at certain stations (e.g., due to technical problems in the acquisition) using  
306 their two closest neighboring station records using linear interpolation. For example, if  
307 TE10 has a missing trace, we interpolate it only when TE09 and TE11 have non-missing  
308 traces for that time. In Figure 7, we show the number of interpolated traces (what we  
309 also call events).

## 310 **LEPC SI Applications**

### 311 **Crosscorrelation and Crosscoherence Processing**

312 We apply crosscorrelation to the preprocessed data of the T-array from MalARRgue after  
313 applying amplitude normalization per coda-wave window per station. The normalization  
314 is used to bring per station the correlation results from each local earthquake to a compa-  
315 rable amplitude and thus to let each correlation have the same weight in the summation  
316 over the earthquakes. We test utilization of energy normalization, normalization by the  
317 maximum amplitude, and normalization by the maximum amplitude followed by spectral  
318 whitening. In Figures 8b-d, we show the three respective results obtained from autocor-  
319 relation, which represent retrieved zero-offset traces. In Figure 8a, we show the retrieved  
320 zero-offset trace obtained without any normalization. As can be seen from Figures 8a-c,  
321 there is no significant difference between the results with and without normalizations, im-  
322 plying that for the earthquakes we choose, the recordings from the different earthquakes  
323 have comparable amplitudes in the 1-5 Hz frequency band. Nevertheless, we can notice  
324 small differences among the results, so it is better to use normalization before correla-  
325 tion given its numerical robustness. In Figure 8e, we show the retrieved zero-offset trace  
326 obtained from autocoherecence. In Figure 8d, we show for completeness of comparison an-  
327 other correlation result obtained after energy normalization and spectral whitening. The



328 whitening was performed using a running window of 0.025 Hz width. Note that energy  
329 normalization followed by spectral whitening makes the result retrieved by correlation  
330 (Figure 8d) close to the one retrieved by coherence (Figure 8e). This is because normal-  
331 ization and spectral whitening mathematically approximates coherence. In this study, we  
332 use crosscorrelation and crosscoherence. For retrieval using crosscorrelation, we choose  
333 to use preprocessing by energy normalization without spectral whitening (as in Figure  
334 8b), so that we could see clear differences between the results from crosscorrelation and  
335 those from crosscoherence.

336 Figures 9a and 9d show retrieved common-source gathers (at positive and negative  
337 times) obtained using crosscorrelation for a virtual source at TN11 (the middle station  
338 in the TN-array) and TE07 (the middle station in the TE-array), respectively. It can  
339 be seen that the common-source gathers exhibit asymmetrically retrieved events with  
340 respect to two-way traveltimes 0 s, indicating that the coda we use is not illuminating the  
341 stations equally from all directions. Even though Mayeda et al. (2007), Baltay et al.  
342 (2010), and Abercrombie (2013) assumed apparent weak to no directivity of the coda,  
343 i.e., isotropic energy flux, due to the expected averaging out of radiation pattern of the  
344 earthquake, Paul et al. (2005) and Emoto et al. (2015) found that the energy flux of  
345 the coda is not isotropic. In the case that the coda has no directivity, the causal and  
346 acausal parts of the common-source gathers obtained from crosscorrelation would result  
347 in a purely symmetric gather. When the coda has directivity, the common-source gather  
348 would exhibit asymmetry as shown in Figure 9d.

349 A possible explanation of the directivity in the coda, which is most likely the case  
350 with our data as well, is that it is associated with the direct-wave passages (e.g., Emoto  
351 et al., 2015). Emoto et al. (2015) discussed that the coda consists of forward scattered  
352 waves (early coda), which have directivity, and multiply scattered waves (later coda),  
353 which have no directivity.

354 For the results retrieved from SI by crosscorrelation and crosscoherence, we correct

355 for the asymmetric results (Figures 9a and 9d) by combining part of the positive and  
356 parts of the negative times as follows. To obtain a final retrieved common-source gather,  
357 we use the acausal part of the retrieved result for traces to the west of the virtual-source  
358 position, reverse this part in time, and concatenate it to the causal part of the retrieved  
359 result for traces to the east of the virtual-source position (Figures 9b and 9e). This pro-  
360 cessing is strictly valid for horizontally layered medium. In our case, since we rely on  
361 secondary scattering, we can still use this processing provided that the scattering results  
362 in the illumination of the array mainly from the west of the array and that the structures  
363 below the array are not complex.

364 For the next processing step, we apply a deterministic spiking deconvolution to re-  
365 move the STF of the retrieved virtual source from each of the retrieved common-source  
366 gathers. The deterministic spiking deconvolution is a technique that compress the STF  
367 (e.g., known from observation) using the least-squares method. The STF are estimated  
368 from the retrieved zero-offset traces at each virtual-source position by extracting a time-  
369 window around time 0 s (Figure 10). Following the conventional seismic processing, we  
370 mute the first breaks and all the events above them from the common-source gathers for  
371 the both TN- and TE-array as shown in Figure 11. Our estimates of the first breaks are  
372 about 3400 m/s (a constant velocity) for both arrays. After that, we re-sort the traces into  
373 CMP gathers and apply normal moveout velocity analysis to the data using semblances.  
374 In Figure 12, two examples of velocity semblance are shown with the regional velocity  
375 model by Farías et al. (2010) indicated by the dashed magenta lines. There is a good cor-  
376 respondence between the regional model and peaks in the middle part of the semblance.  
377 For example, the bright spots in the semblance around 10-11 s (the left panels in Figure  
378 12) correspond to the range of the possible Moho velocity in Farías et al. (2010). In this  
379 study, though, we use for normal-moveout correction and migration the regional velocity  
380 model from Farías et al. (2010) because this simplifies the interpretation during the com-  
381 parison of the current result with our previous result from application of global-phase SI

382 (Nishitsuji et al., 2016). The global-phase SI is an autocorrelation SI that uses global  
383 phases (e.g., *PKiKP*).

384 After obtaining stacked sections along both arrays we apply predictive deconvolution  
385 to suppress possible multiples from the top basement using the estimated depth of the top  
386 of basement beneath MalARRgue (Nishitsuji et al., 2014). Finally, we apply Kirchhoff  
387 post-stack time migration (KTM; Yilmaz, 1987) to move dipping structures to their true  
388 location in the model. As a final processing step, we apply lateral regularization in the  
389 horizontal direction to obtain better imaging in terms of structural interpretation. For the  
390 lateral regularization, we use smoothed discretized splines determined by the generalized  
391 cross-validation (Garcia, 2010). The stacked sections before and after the mentioned  
392 processing (predictive deconvolution, KTM, and lateral regularization) for the TN- and  
393 TE-array are shown in Figures 13a,b and 14a,b, respectively.

394 The seismic processing of the results retrieved from SI by crosscoherence is the same  
395 as for the results retrieved by crosscorrelation, except for the step of applying spiking  
396 deconvolution of the STF, which is not needed. The processed stacked section obtained  
397 from SI by crosscoherence are displayed in Figures 13c and 14c. For Figures 13c and  
398 14c, we select the results obtained using a stabilization factor of 1 % of the maximum in  
399 the amplitude spectrum. In our case, we did not see significant differences when using  
400 stabilization factors between 1 % and 5 %.

#### 401 **MDD Processing**

402 The data processing for application of SI by MDD differs only in a few steps from  
403 the other two LEPC (crosscorrelation and crosscoherence), interferometric applications.  
404 Due to the fact that MDD intrinsically deconvolves for the STF of the earthquake sources  
405 and compensates for directivity in the illumination, neither spiking deconvolution for the  
406 STF of the retrieved virtual source nor selective utilization of parts of the causal and  
407 acausal times are needed. Instead, it is necessary to obtain the estimated PSF for solving

408 the inverse problem of the approximated MDD in equation (11). In Figures 9c and 9f, we  
409 show two examples of PSFs extracted (cut away with tapered edges) from the retrieved  
410 crosscorrelation results in Figures 9a and 9d, respectively. We extracted the PSF with  
411 a butterfly-shaped window around  $t = 0$  and narrowest for  $\mathbf{x}_A = \mathbf{x}_B$ . It aims to include  
412 events obtained from the crosscorrelation between waves that are recorded at the surface  
413 as direct waves from secondary sources in the subsurface (the scatterers and reflectors).  
414 Note that the approximated PSFs are shown after amplitude normalization among the  
415 stations for the purpose of displaying only; we do not use amplitude normalization for  
416 the actual MDD processing. The time window for the PSF is based on the velocity used  
417 for the first-break muting in Figure 12.

418 We apply SI by MDD to the LEPC data using the truncated SVD approach to stabilize  
419 the inversion. We process the two lines separately - we retrieve virtual-source response  
420 along the TN-array using the events recorded by and interpolated along the TN-array;  
421 we retrieve virtual-source response along the TE-array using the events recorded by and  
422 interpolated along the TE-array. As can be seen from Figure 7, the number of earthquakes  
423 for each station per subarray is different. For example, for the TE-array, the number of  
424 interpolated events per station is between 200 and 210. This means that several PSFs  
425 for the TE-array contain zeros for the matrix inversion. However, we expect that the  
426 illumination compensation for the TE-array from the used 210 events will be affected  
427 only to a small degree by the zeros in the PSFs due to the random distribution of the  
428 zeros. The same can be said for the TN-array as well, but in its case the number of  
429 interpolated events per station is around 115 (except for TN02). After the SVD, we  
430 truncate singular values with amplitudes with a threshold value of 10 % of the maximum  
431 singular value. The singular values under the threshold are considered negligible to  
432 retrieve reflection-data estimates. Figure B1 is available in Appendix B that shows the  
433 singular values we truncate. The discarded singular values would largely contribute to  
434 the ill-posedness of equation (11). In Figures 15a and 15b we show the obtained MDD

435 results in the f-x domain for virtual shots at TN11 and TE07, respectively. We also test  
436 application of SI by MDD using the damped least-squares stabilization with a constant  
437 stabilization factor for all frequencies, but the results are not as well stabilized as the  
438 ones using the truncated SVD scheme (Figure 15).

## 439 **Results and Interpretation**

440 In Figures 16 and 17, we show the LEPC SI results for the TN- and TE-array, respec-  
441 tively, obtained by MDD using the truncated SVD; we compare these results to the re-  
442 sults obtained by global-phase SI by Nishitsuji et al. (2016) who used frequency band  
443 0.3-1 Hz. We design the processing parameters for the basement predictive deconvolu-  
444 tion based on the estimated two-way traveltime of the basement multiples (Nishitsuji et  
445 al., 2014). For comparison purposes, we use the same processing parameters of KTM  
446 for both of the LEPC SI and the global-phase SI results. The reflection imaging ex-  
447 hibits more details than the results from the global-phase SI. The bifurcated Moho and  
448 the magma chamber indicated in Figures 16 and 17 are after Gilbert et al. (2006). The  
449 gray shades in Figures 16 and 17 indicate the offset where the CMP fold numbers are less  
450 than or equal to 5; we do not interpret the results inside the gray shaded areas as we deem  
451 this fold insufficient for imaging. The yellow dashed lines are our structural interpreta-  
452 tion where the amplitude and phase discontinuities are seen based on the global-phase  
453 SI results. We superimpose those interpreted features over the LEPC SI results because  
454 it is difficult to tell which features are the artifacts or not in a decisive way. Although  
455 one might like to interpret more structures on the LEPC SI results, we only focus on  
456 the major features interpreted by the global-phase SI results. Because we would like to  
457 keep the correspondence, no horizon interpretations are given for structures shallower  
458 than about 7-seconds two-way traveltime, where the global-phase SI results become un-  
459 clear (Figures 16b and 17b). The global-phase SI results (Figures 16b and 17b) show the  
460 limitation in interpreting shallow structures because the subtraction of the average STF

461 for 10 s unavoidably removes some shallow structures. Note that because LEPC SI has  
462 retrieved reflections that resulted in imaging structures below the array, we can conclude  
463 that there has been sufficient local scattering below the array. This is also expected from  
464 the presence of a line of volcanic cones at the surface crossing the TE-array. Local sec-  
465 ondary scattering from structures below the array would result in arrivals characterized  
466 by small emergence angles at the array; such arrivals will be turned by SI into reflections.  
467 As the local earthquakes we use are distanced from the TN- and TE-arrays and the coda  
468 window length is limited, if there were little or no local scattering below the array, LEPC  
469 SI would not have retrieved reflections.

470 Since all of the LEPC SI results (crosscorrelation, crosscoherence, and MDD) appear  
471 in general to be similar (see Figures 13b-d and 14b-d), one might prefer to use for the  
472 interpretation of the other LEPC SI results instead the MDD results. However, if we have  
473 a limited number of local earthquakes whose back-azimuth coverage is insufficient with  
474 respect to the receiver-array, MDD should in theory work better than the other two meth-  
475 ods (Nakata et al., 2014). This is, because for crosscorrelation and crosscoherence to  
476 work, a large number of local earthquakes with sufficiently wide back-azimuth coverage  
477 is essential for the effective suppression of the cross-talk (e.g., Snieder, 2004; Snieder et  
478 al., 2006). On the other hand, assuming a sufficiently good coverage of the local earth-  
479 quakes is available but the receiver-array is patchy or irregular, both the crosscorrelation  
480 and crosscoherence would work, whereas MDD would be ill-posed because it requires  
481 regularly-spaced receivers. As shown in Figures 1 and 2, we have good coverage of  
482 the local earthquakes recorded at the exploration-type array. This could be the reason  
483 why the LEPC SI results in Figures 13b-d and 14b-d show similar results at our scale of  
484 interest. Nevertheless, we decide to select the LEPC SI results based on the MDD by  
485 truncated SVD scheme in Figures 16 and 17 rather than the others because we find that  
486 a few structural features showing more continuity in space. For instance, a horizontal  
487 coherent feature around 8 s in Figure 16 and up-dipping (from west to east direction)

488 structures between 13-15 s in Figure 17 are clearer than the images from the other two  
489 methods in Figures 13 and 14. More importantly, the PSFs in Figure 15 are smeared in  
490 space and time, which means that the crosscorrelation results in Figures 13 and 14 are  
491 biased due to the spatial-temporal blurring effect of the PSF. This is also the reason we  
492 select the MDD results in Figures 16 and 17.

493 Interpreting results from the magnetotelluric method, Burd et al. (2014) (the blue  
494 dashed line in Figure 1) recently suggested the presence of a possible shallow astheno-  
495 spheric plume (e.g., 0-100 km in depth) nearby the Peteroa volcano. The authors in-  
496 terpreted this shallow plume as possibly connected to the main upwelling plume whose  
497 origin would be around the mantle transition zone (410-660 km in depth). Gilbert et al.  
498 (2006) showed the receiver-function imaging at roughly 50 km south of MalARRgue,  
499 interpreting a possible bifurcation of the Moho with magma chamber in between (Figure  
500 5 in Gilbert et al., 2006). The study by Nishitsuji et al. (2016) using the global-phase  
501 SI confirmed such Moho bifurcation beneath the array of the MalARRgue. Summing up  
502 the above interpretations, one could expect a dynamic tectonic regime rather than a static  
503 one in this Andean region.

504 As we described earlier, the reflection imaging of the LEPC SI results exhibits more  
505 details than the results from the global-phase SI. As shown by Abe et al. (2007) and  
506 Nishitsuji et al. (2016), the vertical imaging resolution in results retrieved by SI would  
507 be at least as high as, but potentially higher, than the ones obtained by the receiver-  
508 function method. The difference of the resolution in Figures 16 and 17 is largely due  
509 to the difference in the used frequency band. Nishitsuji et al. (2016) used global-phase  
510 earthquakes with frequency band 0.3-1 Hz, whereas here we use 1-5 Hz for the LEPC  
511 SI results. In addition to the correspondence (or similarity) of the structural features (the  
512 yellow dashed lines in Figures 16 and 17) between these two different methods, there  
513 is another striking feature - a possible major fault in Figure 17a, indicated by the green  
514 dashed line, where horizon displacements can be seen. According to the active-seismic

515 reflection profile (the green solid line in Figure 1) and nearby exploration well (LPis x-1)  
516 given in Kraemer et al. (2011), deep basement thrust faults, which are reverse faults (see  
517 Figure 8a in Kraemer et al., 2011), are expected to exist in this region as a typical feature  
518 of foredeep basins (DeCelles and Giles, 1996). Such thrust faults can also be seen in  
519 Gimbiagi et al. (2009) and Giambiagi et al. (2012) in their Figures 7b-c and 2 (e.g.,  
520 cross-section H), respectively. Because the reverse faults beneath LPis x-1 are thought  
521 to be dipping to the west, identifying such faults below the TE-array (Figure 17a), but  
522 not below the TN-array (Figure 16a) is logical. Thus, we interpret the feature indicated  
523 by the green dashed line in Figure 17a as possibly corresponding to one of those deep  
524 thrusts.

525 The blue ellipses in Figure 17 indicate zones where dimmed-amplitude portions can  
526 be seen in both the LEPC SI (Figure 17a) and global-phase SI results (Figure 17b). Since  
527 both independent methods use acoustic SI approaches, such dimming features might  
528 indicate weaker reflection responses in comparison with the other zones. Referring to  
529 the previous studies in this region, such weaker reflectivity might be due to the presence  
530 of the shallow asthenospheric plume that has been interpreted by Burd et al. (2014).  
531 Otherwise, such dimmed amplitudes might be indicative of partial-melting spots that are  
532 only locally present.

533 We also observe that the Moho in the LEPC SI results are not as visually dominant as  
534 the ones from the global-phase SI (Nishitsuji et al., 2016) and receiver-function method  
535 (Gilbert et al., 2006). This feature could be also found in other high-resolution reflection  
536 images by active-seismic sources. For instance, although the reflection results in Singh et  
537 al. (2006) and Calvert and McGeary (2013) provided very fine scale of the images (e.g.,  
538 50 m in depth after Singh et al., 2006), we find that the Moho in their results is somewhat  
539 less prominent than in the image from seismic tomography (e.g., Calvert et al., 2011)  
540 and the receiver-function method (e.g., Gilbert et al., 2006). This is probably because  
541 the Moho discontinuity is rather better sensed with low frequencies (e.g.,  $\leq 1$  Hz). The



542 active-source reflection in Singh et al. (2006) and LEPC SI in this study used 10-30  
543 Hz and 1-5 Hz, respectively. The seismic tomography in Calvert et al. (2011) and the  
544 global-phase SI in Nishitsuji et al. (2016) used 0.03-0.3 Hz and 0.3-1 Hz, respectively.

545 Therefore, as long as one's goal is the identification of the Moho, using the lower fre-  
546 quencies would in general be sufficient. Still, LEPC SI can provide useful information at  
547 low acquisition cost when finer structural imaging and/or shallower targets are of interest  
548 (e.g., basin imaging if one can use higher frequency). For the current imaging resolu-  
549 tion, LEPC SI could even assist in enhanced geothermal-system exploration together  
550 with magnetotelluric investigations. It is of importance for enhanced geothermal-system  
551 explorations to estimate the deeply lying conductive feature and the possible fault sys-  
552 tem between the thermal source (e.g., Moho) and the target basement (up to 10 km).  
553 The success of the method depends on the illumination of the receiver array by the coda  
554 wavefield. In our case, the results show illumination directivity at the TE-array for the  
555 coda-waves part we use. The main advantage of the method is that it turns the passive  
556 recordings into reflection recordings, which is not possible without using SI. Note that  
557 active-source measurements in the frequency bandwidth we use in this study are not al-  
558 ways available. In this case, LEPC SI might complement the low-frequency bandwidth  
559 and would be a useful alternative approach.

## 560 **Conclusions**

561 We presented seismic interferometry for P-wave coda from local earthquakes (LEPC SI)  
562 in order to obtain crustal-scale reflection imaging without active sources. We applied  
563 LEPC SI with a linear array in the Malargüe region, Argentina, where a part of the  
564 Neuquén basin exists underneath. We compared SI by crosscorrelation, crosscoherence,  
565 and MDD, each followed by standard seismic processing from exploration seismology.  
566 For the MDD method, we found the truncated SVD scheme gave a more stable solution  
567 of the matrix inversion than the one by damped least-squares. This MDD result pro-

568 vided us slightly better structural imaging at our scale of interest among all LEPC SI  
569 approaches we investigated. We also interpreted not only the deep thrust fault but also  
570 possible melting zones that are previously suggested by active-seismic (including explo-  
571 ration well) as well as magnetotelluric surveys. Depending on the frequency-bandwidth,  
572 the availability of the local earthquakes, and the spatial sampling of receivers, LEPC SI  
573 has a potential to reveal not only the crustal-scale structure but also lithospheric-scale or  
574 basin-scale structures.

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592 (GMT) (Wessel and Smith, 1991) and MATLAB.

## 593 Appendix A

594

### 595 **Approximated Multidimensional Deconvolution (MDD)**

596 Here, we show the derivation to obtain the approximate expression for seismic inter-  
 597 ferometry (SI) by MDD - equation (5) in the main text. First, we define the following  
 598 relation in the frequency domain  $\omega$ :

$$\bar{v}_z(\mathbf{x}_B, \omega) = \bar{v}_z^d(\mathbf{x}_B, \omega) + \bar{v}_z^c(\mathbf{x}_B, \omega), \quad (1)$$

599 where  $\bar{v}_z(\mathbf{x}_B, \omega)$  is the vertical component ( $z$ ) of the particle velocity vector in the absence  
 600 of a free surface at the receiver  $\mathbf{x}_B$  for a local earthquake in the subsurface,  $\bar{v}_z^d(\mathbf{x}_B, \omega)$   
 601 represents only the direct arrival, and  $\bar{v}_z^c(\mathbf{x}_B, \omega)$  represents the coda i.e., the scattering  
 602 between inhomogeneities inside the medium. For the situation where there is a free  
 603 surface at the receiver level, we also define the following relation:

$$v_z(\mathbf{x}_B, \omega) = v_z^d(\mathbf{x}_B, \omega) + v_z^c(\mathbf{x}_B, \omega), \quad (2)$$

604 which is the free-surface counterpart of equation (A-1). Note that  $v_z^c(\mathbf{x}_B, \omega)$  is the coda  
 605 wavefield we actually observe (see the light blue shades in Figure 6). Taking into account  
 606 the fact that  $v_z^d(\mathbf{x}_B, \omega) = 2\bar{v}_z^d(\mathbf{x}_B, \omega)$ , equation (A-2) can be rewritten as

$$v_z(\mathbf{x}_B, \omega) = 2\bar{v}_z^d(\mathbf{x}_B, \omega) + v_z^c(\mathbf{x}_B, \omega). \quad (3)$$

607 Using equations (A-1) and (A-3), we can write for the scattered field

$$v_z^{scatt}(\mathbf{x}_B, \omega) = v_z(\mathbf{x}_B, \omega) - 2\bar{v}_z(\mathbf{x}_B, \omega) = v_z^c(\mathbf{x}_B, \omega) - 2\bar{v}_z^c(\mathbf{x}_B, \omega). \quad (4)$$

608 Here, we recall equation (63) in Wapenaar et al. (2011):

$$v_z^{scatt}(\mathbf{x}_B, \omega) = A \iint_{\partial D_0} G_{z,z}^{scatt}(\mathbf{x}_B, \mathbf{x}, \omega) \bar{v}_z(\mathbf{x}, \omega) d^2\mathbf{x}, \quad (5)$$

609 where  $G_{z,z}^{scatt}$  is the scattered Green's function and  $A$  is an amplitude-scaling factor due  
 610 to the approximation that  $\bar{v}_z(\mathbf{x}, \omega)$  under the integral is proportional to the pressure mea-  
 611 surement. The integral in equation (A-5) is taken along the receiver positions (Earth's  
 612 surface  $\partial D_0$ ). Substituting equations (A-1) and (A-4) into equation (A-5), we get

$$v_z^c(\mathbf{x}_B, \omega) - 2\bar{v}_z^c(\mathbf{x}_B, \omega) = A \iint_{\partial D_0} G_{z,z}^{scatt}(\mathbf{x}_B, \mathbf{x}, \omega) \left\{ \bar{v}_z^d(\mathbf{x}, \omega) + \bar{v}_z^c(\mathbf{x}, \omega) \right\} d^2\mathbf{x}. \quad (6)$$

613 Multiplying equation (A-6) with  $\bar{v}_z^c(\mathbf{x}_A, \omega)^*$  and summation over the available sources,  
 614 we get

$$\sum_{S=1}^n \left[ v_z^c(\mathbf{x}_B, \omega) \left\{ \bar{v}_z^c(\mathbf{x}_A, \omega) \right\}^* \right] - 2\Gamma(\mathbf{x}_B, \mathbf{x}_A, \omega) = \quad (7)$$

$$A \iint_{\partial D_0} G_{z,z}^{scatt,d}(\mathbf{x}_B, \mathbf{x}, \omega) \left[ \sum_{S=1}^n \left[ \bar{v}_z^d(\mathbf{x}, \omega) \left\{ \bar{v}_z^c(\mathbf{x}_A, \omega) \right\}^* \right] + \Gamma(\mathbf{x}, \mathbf{x}_A, \omega) \right] d^2\mathbf{x},$$

615 where  $*$  denotes the complex conjugate and  $\Gamma$  is the point-spread function (PSF, Wape-  
 616 naar et al., 2011) defined as

$$\Gamma(\mathbf{x}_B, \mathbf{x}_A, \boldsymbol{\omega}) = \sum_{S=1}^n [\bar{v}_z^c(\mathbf{x}_B, \boldsymbol{\omega}) \{\bar{v}_z^c(\mathbf{x}_A, \boldsymbol{\omega})\}^*]. \quad (8)$$

617 Equation (A-7) can be also written as

$$\sum_{S=1}^n [v_z^c(\mathbf{x}_B, \boldsymbol{\omega}) \{v_z^c(\mathbf{x}_A, \boldsymbol{\omega})\}^*] - 2\Gamma(\mathbf{x}_B, \mathbf{x}_A, \boldsymbol{\omega}) + \sum_{S=1}^n [v_z^c(\mathbf{x}_B, \boldsymbol{\omega}) [\{\bar{v}_z^c(\mathbf{x}_A, \boldsymbol{\omega}) - v_z^c(\mathbf{x}_A, \boldsymbol{\omega})\}^*]] - \quad (9)$$

$$A \iint_{\partial D_0} G_{z,z}^{scatt,d}(\mathbf{x}_B, \mathbf{x}, \boldsymbol{\omega}) \sum_{S=1}^n [\bar{v}_z^d(\mathbf{x}, \boldsymbol{\omega}) \{\bar{v}_z^c(\mathbf{x}_A, \boldsymbol{\omega})\}^*] d^2\mathbf{x} = A \iint_{\partial D_0} G_{z,z}^{scatt,d}(\mathbf{x}_B, \mathbf{x}, \boldsymbol{\omega}) \Gamma(\mathbf{x}, \mathbf{x}_A, \boldsymbol{\omega}) d^2\mathbf{x}.$$

618 The third and fourth terms in the left-hand side of equation (A-9) retrieve events that  
 619 are already retrieved by the first term in the left-hand side. Thus, the third and fourth  
 620 terms can be seen as amplitude corrections to the events retrieved by the first term. If  
 621 we neglect them to obtain equation (5), we will not obtain correct amplitudes in the left-  
 622 hand side of equation (A-9) and we will introduce artifacts. Still, the MDD of the first  
 623 two terms in the left-hand side by  $\Gamma$  will result in the compensation of the result retrieved  
 624 from SI by crosscorrelation for inhomogeneous illumination. Furthermore, as  $\Gamma$  cannot  
 625 be obtained directly, we approximate it by only the dominant arrivals in the result from  
 626 SI by crosscorrelation (see for examples Figures 9c and 9f).

## 627 Appendix B

### 628 Truncated Singular-Value Decomposition (SVD)

629 In Figure B1, we show the truncated singular values for the TN- and TE-array.

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## 852 **Figure Captions**

### 853 **Figure 1.:**

854 Distribution map of the local earthquakes ( $2^\circ \leq$  epicentral distance  $\leq 6^\circ$ ) used in our  
855 study. The 115 circles and 210 stars show the locations of the earthquakes recorded by  
856 the TN- (the white triangles) and TE-array (black triangles) parts of the MalARRgue  
857 array; the earthquakes are color-scaled as a function of their focal depth. The volcano  
858 symbol indicates the location of the Peteroa volcano. The green outline indicates an  
859 approximated location of the Neuquén basin (derived from Mescua et al., 2013). The  
860 blue polygon indicates an approximated location of the lake Llanquanelo. The magenta  
861 solid and blue dashed lines indicate the location at which active-source seismic and an

862 magnetotelluric sections are obtained by Kraemer et al. (2011) and Burd et al. (2014),  
863 respectively, which are discussed in Results and Interpretation of this paper.

864 **Figure 2.:**

865 Distribution of the back azimuth of the local earthquakes recorded by the TN-array and  
866 TE-array.

867 **Figure 3.:**

868 A schematic illustration of equation (5).

869 **Figure 4.:**

870 Power spectral densities for a local earthquake with  $M_b$  4.0. The power spectral densities  
871 are computed for the TE-array.

872 **Figure 5.:**

873 Used window length of the P-wave coda as a function of epicentral distance. The trav-  
874 eltime curves are drawn using the regional velocity model from Farías et al. (2010) for  
875 depths down to 110 km and the ak135 model (Kennett et al., 1995) for greater depths.  
876 Light gray rectangular indicates the used epicentral distance, while the dark gray area  
877 indicates the the window lengths to be extracted for an earthquake characterized by a  
878 source depth of 100 km.

879 **Figure 6.:**

880 An example recording of a local earthquake on the vertical (left panel) and transverse  
881 component (right panel) of the stations from the TN-array. The areas highlighted in  
882 orange indicate the direct P-wave arrival from the local earthquake, while the green lines

883 indicates the S-wave onset. The area highlighted in light blue indicates the P-wave coda  
884 to be extracted.

885 **Figure 7.:**

886 Number of original and interpolated events for each of the TN- and TE-array stations.

887 **Figure 8.:**

888 Retrieved zero-offset trace at station TE07 of the TE-array obtained using (a) autocorre-  
889 lation without amplitude normalization, (b) energy normalization before autocorrelation,  
890 (c) maximum-amplitude normalization before autocorrelation, (d) maximum-amplitude  
891 normalization followed by spectral whitening before autocorrelation, and (e) autocohere-  
892 nce.

893 **Figure 9.:**

894 Retrieved common-source gather for a virtual source at (a) station TN11 of the TN-array  
895 before flipping, (b) after flipping the negative times, (d) station TE07 of the TE-array  
896 before flipping, (e) after flipping the negative times. The PSFs of (c) and (f) are extracted  
897 from the gray shaded areas in figures (a) and (d), respectively. The results are retrieved  
898 using correlation and after summation over the used local earthquakes.

899 **Figure 10.:**

900 Retrieved zero-offset traces using all events from (a) the TN-array (c) the TE-array. (b)  
901 and (d) are estimated source time functions from the zero-offset traces in (a) and (c),  
902 respectively, after application of time windowing.



903 **Figure 11.:**

904 A comparison of common-source gather: for station TN11 of the TN-array (a) before  
905 spiking deconvolution and muting the first breaks and (b) after spiking deconvolution and  
906 muting the first breaks and above; for station TE07 of the TE-array (c) before spiking  
907 deconvolution and muting the first breaks and (d) after spiking deconvolution and muting  
908 the first breaks and above.

909 **Figure 12.:**

910 Examples of velocity semblance of common midpoint gather for station TN11 of the  
911 TN-array (left panels) and station TE07 of the TE-array (right panels) with the regional  
912 velocity model of Farías et al. (2010) denoted by the magenta dashed lines.

913 **Figure 13.:**

914 A comparison of LEPC SI results for the TN-array using different SI theories: (a) cross-  
915 correlation after basement deconvolution without KTM; (b) same as (a) but with KTM;  
916 (c) same as (b) but for crosscoherence; (d) same as (b) but for MDD using the truncated  
917 SVD scheme.

918 **Figure 14.:**

919 Same as Figure 13 but for the TE-array.

920 **Figure 15.:**

921 Obtained MDD results using the damped least-square and the truncated SVD scheme in  
922 the f-x domain for virtual shots at: (a) station TN11; (b) station TE07 in comparison with  
923 the crosscorrelation (Figures 9a and 9d) and the PSF (Figures 9c and 9f).

924 **Figure 16.:**

925 Summarized interpretation on the crustal-scale reflection images beneath the TN-array  
926 obtained from: (a) LEPC SI (1-5 Hz) with the truncated MDD scheme; (b) global-phase  
927 SI (0.3-1 Hz) modified from Nishitsuji et al. (2016). The interpretation of the Moho  
928 and the magma chamber are after Gilbert et al. (2006) and Nishitsuji et al. (2016). The  
929 yellow dashed lines indicate our structural interpretation that can be traced for both the  
930 MDD and the global-phase SI results. The gray shades are the offset where the CMP  
931 folds are less than equal to 5. The cyan ellipses indicate the amplitude pockets that can  
932 be commonly interpretable between the MDD and the global-phase SI results.

933 **Figure 17.:**

934 Same as Figure 16, but for the TE-array. The blue ellipses indicate the dimming imaging  
935 parts that can be commonly interpretable between the MDD and the global-phase SI  
936 results. The green dashed line indicates our fault interpretation where the major deep  
937 thrust fault can be traced.

938 **Figure B1.:**

939 Truncated singular values for the TN- and TE-array. The white lines show where 10 %  
940 of the maximum singular value lie. We truncate the lower amplitude within the white  
941 line for MDD.

Table 1. Local earthquakes used in this study

Date (month/d/yr)	Time (hr:min:s)	Lat. (°N)	Lon. (°E)	Dep. (km)	$M_s$	Array ID
01/17/12	15:09:02	-30.814	-71.214	75	3.9	TE
01/17/12	23:21:34	-31.605	-71.686	31	5.5	TE
01/18/12	3:17:16	-31.589	-71.789	50	4.7	TE
01/18/12	11:33:03	-31.798	-68.397	10	4.6	TE
01/18/12	11:35:52	-31.665	-68.164	19	5.0	TE
01/19/12	3:58:17	-31.756	-68.657	15	4.6	TE
01/19/12	7:10:20	-31.635	-71.898	38	4.9	TE
01/19/12	8:22:49	-32.193	-71.213	87	3.9	TE
01/20/12	5:26:33	-31.273	-71.736	49	3.4	TE
01/20/12	6:05:41	-31.982	-68.843	117	3.5	TE
01/23/12	16:04:53	-36.455	-73.182	24	5.8	TE
01/23/12	16:29:30	-36.380	-73.267	25	4.0	TE
01/23/12	16:30:55	-36.457	-73.023	25	3.9	TE
01/23/12	17:22:06	-36.344	-73.443	4	5.0	TE
01/23/12	17:53:45	-36.472	-73.365	6	4.4	TE
01/23/12	21:55:15	-36.364	-73.304	28	5.0	TE
01/24/12	1:45:28	-34.525	-71.949	40	4.5	TE
01/24/12	16:08:48	-31.651	-67.078	150	3.7	TE
01/24/12	17:07:49	-31.760	-72.416	9	4.6	TE
01/26/12	2:23:10	-29.325	-68.081	118	3.6	TE
01/26/12	4:57:07	-34.831	-72.498	19	3.9	TE
01/27/12	2:24:10	-34.708	-71.824	17	4.1	TE
01/31/12	13:08:00	-33.817	-72.135	12	4.6	TE
01/31/12	19:40:03	-33.876	-71.997	18	4.0	TE
01/31/12	21:24:05	-32.788	-71.712	39	3.3	TE
02/01/12	2:43:19	-32.678	-71.336	52	4.8	TE
02/01/12	2:43:25	-32.950	-70.256	40	4.7	TE
02/01/12	2:43:27	-33.053	-70.851	44	4.7	TE
02/04/12	10:12:55	-38.551	-74.433	35	4.2	TE
02/05/12	3:42:08	-36.690	-73.243	38	4.7	TE
02/07/12	12:02:11	-37.902	-74.974	18	4.9	TE
02/10/12	2:05:22	-30.791	-71.304	57	4.9	TE
02/10/12	4:07:51	-30.735	-71.222	38	3.8	TE
02/11/12	2:58:17	-37.456	-73.884	20	5.6	TE
02/11/12	8:41:14	-36.851	-72.860	40	4.0	TE
02/14/12	5:58:02	-32.010	-70.034	103	4.5	TE
02/14/12	8:19:27	-34.948	-71.684	52	4.5	TE
02/15/12	7:36:14	-34.665	-72.958	10	4.4	TE
02/15/12	14:08:47	-35.209	-73.926	19	4.7	TE
02/16/12	22:01:46	-37.255	-74.245	5	4.2	TE
02/17/12	8:01:14	-37.208	-74.313	17	4.8	TE
02/17/12	8:01:19	-37.175	-73.646	14	4.8	TE
02/17/12	19:11:23	-37.233	-73.785	35	4.3	TE
02/18/12	2:06:27	-34.547	-72.098	29	4.5	TE
02/18/12	3:50:49	-37.104	-72.316	35	4.0	TE
02/18/12	17:44:48	-32.097	-71.771	18	4.9	TE
02/22/12	15:03:39	-33.089	-71.785	33	4.5	TE
02/22/12	22:38:40	-34.765	-71.809	47	4.0	TE
03/01/12	6:44:27	-38.331	-73.585	35	4.2	TE
03/01/12	18:41:47	-31.572	-69.273	96	4.6	TE
03/03/12	11:01:47	-30.348	-71.129	49	5.5	TE
03/03/12	22:12:55	-35.749	-72.800	13	4.9	TE
03/03/12	22:45:40	-35.731	-72.966	10	4.7	TE
03/03/12	23:41:30	-35.528	-72.726	28	4.6	TE
03/03/12	23:43:04	-35.740	-72.975	10	4.9	TE
03/09/12	0:43:36	-34.730	-72.781	39	4.3	TE
03/12/12	19:37:36	-34.969	-71.664	70	4.9	TE
03/16/12	6:20:12	-36.895	-73.596	27	4.7	TE
03/16/12	23:31:54	-33.606	-72.038	46	4.7	TE
03/17/12	1:36:00	-33.480	-72.372	21	4.0	TE
03/21/12	2:41:00	-35.789	-72.029	67	4.6	TE
03/23/12	9:25:32	-31.691	-69.025	95	4.3	TE
03/24/12	7:28:33	-33.052	-71.063	69	5.0	TE
03/25/12	22:37:06	-35.200	-72.217	41	6.5	TE
03/26/12	2:07:41	-34.994	-72.092	35	4.4	TE
03/27/12	2:46:12	-37.002	-73.275	23	4.5	TE
03/28/12	3:23:39	-35.541	-72.998	16	4.7	TE
03/30/12	7:12:52	-35.196	-72.187	38	4.5	TE/TN
03/31/12	21:52:56	-35.267	-72.089	43	4.4	TE/TN
04/01/12	19:09:57	-31.908	-71.322	65	4.9	TE/TN
04/03/12	2:11:03	-33.847	-72.757	32	5.0	TE/TN
04/06/12	1:30:12	-34.766	-71.608	37	3.7	TE
04/06/12	13:25:05	-38.226	-75.019	35	4.9	TN
04/06/12	17:11:27	-36.926	-73.899	10	4.7	TE
04/06/12	21:04:54	-35.598	-72.834	13	4.1	TE/TN
04/07/12	19:13:29	-37.408	-73.870	44	4.4	TE
04/13/12	6:13:16	-35.210	-72.020	40	4.7	TE/TN
04/15/12	18:58:21	-32.385	-71.940	27	4.4	TE/TN
04/16/12	10:34:14	-36.241	-73.352	27	4.3	TE/TN
04/17/12	3:50:16	-32.625	-71.365	29	6.2	TE/TN
04/17/12	4:03:18	-32.553	-71.366	40	4.9	TE/TN
04/17/12	17:53:57	-33.998	-72.342	11	4.1	TE/TN
04/17/12	23:37:36	-32.617	-71.591	25	3.5	TE/TN
04/19/12	1:14:06	-30.868	-71.188	65	4.7	TE/TN
04/21/12	5:14:37	-36.354	-72.709	63	4.0	TE/TN
04/21/12	22:18:11	-38.224	-74.289	31	4.7	TE/TN
04/27/12	17:58:24	-35.121	-71.901	43	4.7	TE/TN
04/27/12	18:34:38	-34.722	-71.721	43	4.7	TE/TN
04/28/12	20:46:48	-32.653	-71.829	5	4.1	TE
04/30/12	7:39:46	-29.868	-71.460	37	5.6	TE/TN
05/01/12	2:43:34	-29.456	-70.770	57	4.6	TN
05/01/12	20:52:14	-30.813	-71.935	22	4.8	TE
05/05/12	23:06:53	-31.474	-69.173	110	4.3	TE/TN
05/10/12	17:11:52	-37.249	-73.914	10	4.4	TE/TN
05/11/12	19:41:21	-32.901	-71.878	13	4.3	TE/TN
05/12/12	5:27:36	-34.896	-71.864	44	4.0	TE/TN
05/12/12	18:15:09	-34.523	-73.269	15	4.7	TE/TN
05/13/12	12:42:50	-32.740	-71.799	12	4.8	TE/TN
05/16/12	9:02:01	-36.901	-70.623	144	4.3	TE
05/16/12	10:15:36	-35.528	-71.312	118	4.3	TE
05/17/12	2:34:14	-31.777	-69.530	97	4.4	TE/TN
05/17/12	6:50:54	-32.697	-71.816	29	4.6	TE/TN
05/18/12	10:33:12	-31.807	-68.348	60	4.4	TE/TN
05/20/12	3:32:00	-30.782	-71.353	48	3.8	TE

05/21/12	5:15:26	-31.263	-68.507	84	4.3 TE/TN
05/21/12	11:13:33	-30.994	-71.648	59	4.4 TE
05/22/12	6:22:01	-32.244	-71.691	31	4.3 TE/TN
05/24/12	19:18:55	-36.912	-70.467	150	5.1 TE

05/31/12	8.27.17	-34.225	-71.751	20	4.5 TE/TN
06/01/12	18.19.52	-31.718	-68.635	19	4.7 TE
06/02/12	21.36.12	-36.174	-73.725	56	4.1 TE
06/07/12	7.40.54	-31.643	-71.219	36	4.7 TE/TN
06/11/12	9.50.59	-37.072	-73.661	40	4.2 TE
06/15/12	5.43.13	-38.188	-74.702	22	4.7 TE/TN
06/18/12	7.46.23	-36.692	-75.280	30	4.2 TE/TN
06/18/12	8.29.04	-33.009	-68.496	23	5.3 TE/TN
06/21/12	9.24.22	-35.523	-72.223	28	4.5 TE/TN
06/23/12	6.39.32	-34.563	-71.919	47	4.2 TE/TN
06/23/12	18.14.21	-31.580	-71.856	42	4.7 TE
06/25/12	13.38.17	-37.970	-74.821	10	4.6 TE/TN
06/26/12	7.09.27	-35.473	-71.676	84	4.5 TE
06/26/12	17.01.37	-37.758	-74.820	35	4.6 TE/TN
06/27/12	13.06.34	-31.701	-67.692	41	4.5 TE
06/27/12	22.04.25	-32.676	-71.722	20	3.9 TE/TN
06/28/12	10.33.17	-36.085	-73.270	30	4.3 TN
06/28/12	11.49.11	-31.447	-66.754	116	4.6 TE/TN
07/04/12	8.33.05	-38.040	-73.288	33	4.7 TE/TN
07/04/12	22.57.16	-37.631	-74.077	21	4.6 TE/TN
07/05/12	5.53.00	-34.494	-72.638	39	3.9 TE/TN
07/07/12	10.52.15	-32.502	-71.600	33	4.8 TE/TN
07/09/12	1.44.27	-35.213	-72.069	50	4.5 TE/TN
07/09/12	12.56.37	-33.061	-68.263	142	4.6 TE/TN
07/09/12	14.24.37	-37.700	-73.870	30	4.3 TE/TN
07/15/12	8.23.25	-33.483	-67.477	200	4.6 TE/TN
07/17/12	22.03.26	-31.298	-71.210	52	4.0 TE
07/30/12	18.49.45	-35.771	-74.163	44	4.8 TE/TN
08/02/12	15.01.32	-31.862	-68.575	20	4.3 TE/TN
08/04/12	13.11.46	-32.835	-69.175	33	4.3 TE/TN
08/04/12	19.05.39	-31.928	-69.358	119	5.0 TE/TN
08/17/12	20.19.54	-35.613	-73.615	20	4.7 TE/TN
08/23/12	19.03.48	-35.776	-73.462	11	4.8 TE/TN
08/24/12	22.30.01	-33.434	-72.310	42	4.7 TE/TN
08/27/12	1.29.45	-31.386	-67.746	105	4.2 TE/TN
08/27/12	4.17.56	-34.709	-71.762	55	4.0 TE/TN
08/28/12	8.11.25	-32.418	-71.169	44	4.8 TE/TN
08/30/12	8.04.40	-37.199	-73.397	23	5.0 TE/TN
09/04/12	5.30.17	-32.516	-69.916	112	4.5 TE/TN
09/06/12	18.58.03	-36.719	-73.408	35	4.7 TE/TN
09/11/12	6.35.38	-31.875	-68.350	124	5.1 TE/TN
09/11/12	7.24.37	-38.001	-73.860	21	4.6 TE/TN
09/12/12	9.20.58	-32.606	-68.692	139	4.6 TE/TN
09/15/12	0.40.16	-34.638	-72.564	34	4.7 TE/TN
09/15/12	0.50.45	-34.622	-72.923	26	4.5 TE/TN
09/15/12	9.37.18	-32.853	-66.601	36	4.6 TE/TN
09/18/12	3.53.30	-31.893	-69.262	26	4.4 TE/TN
09/20/12	10.07.07	-34.436	-71.951	60	4.5 TE/TN
09/21/12	9.22.26	-32.947	-69.739	101	4.4 TE/TN
09/28/12	3.11.50	-31.430	-67.915	96	4.1 TE/TN
09/28/12	19.21.47	-34.603	-73.369	10	4.3 TE
10/01/12	8.06.29	-30.786	-71.184	56	4.6 TE/TN
10/05/12	8.44.51	-34.899	-71.937	60	4.4 TE/TN
10/06/12	3.18.15	-32.132	-72.107	9	4.6 TE
10/06/12	22.49.38	-32.127	-71.860	7	4.3 TE
10/08/12	13.03.42	-34.654	-73.639	14	4.2 TE/TN
10/09/12	3.30.33	-29.393	-69.211	97	4.8 TE/TN
10/10/12	18.05.02	-34.039	-71.675	33	4.1 TE/TN
10/11/12	2.38.30	-34.000	-72.500	32	4.6 TE/TN
10/11/12	4.38.24	-33.996	-72.442	35	4.7 TE/TN
10/11/12	17.22.10	-32.865	-70.310	82	5.5 TE/TN
10/11/12	21.36.08	-34.011	-72.483	43	4.2 TE/TN
10/14/12	3.37.30	-34.606	-72.209	15	4.5 TE/TN
10/14/12	10.50.17	-35.310	-73.932	21	4.8 TE/TN
10/15/12	21.04.21	-31.814	-71.787	24	5.2 TE
10/18/12	4.38.00	-31.827	-72.034	29	4.5 TE
10/18/12	5.23.14	-34.689	-71.906	43	4.2 TE/TN
10/19/12	5.35.22	-31.793	-72.024	43	3.8 TE
10/19/12	22.48.18	-31.758	-71.950	10	4.6 TE
10/20/12	0.25.48	-32.251	-72.141	22	4.4 TE/TN
10/21/12	11.40.36	-37.658	-73.723	15	4.5 TE/TN
10/24/12	3.46.30	-31.698	-72.069	44	4.7 TE
10/25/12	5.37.58	-32.773	-70.165	105	4.8 TE/TN
10/25/12	19.25.41	-29.568	-70.968	69	4.1 TE
10/27/12	12.33.05	-33.642	-72.006	47	4.4 TE/TN
10/28/12	1.43.00	-33.404	-71.608	34	3.9 TE/TN
11/01/12	23.43.38	-31.794	-67.119	109	4.3 TE/TN
11/02/12	23.42.36	-34.848	-71.789	60	4.5 TE/TN
11/04/12	14.33.06	-31.729	-71.885	43	4.2 TE/TN
11/07/12	15.16.27	-30.780	-71.934	34	4.6 TE
11/07/12	18.37.50	-37.948	-73.141	38	4.4 TE
11/07/12	22.41.33	-37.512	-72.985	39	4.8 TE/TN
11/08/12	6.24.10	-32.710	-71.310	46	4.3 TE/TN
11/08/12	23.57.57	-31.882	-69.070	107	4.6 TE
11/09/12	6.31.44	-33.427	-67.479	187	4.1 TE/TN
11/11/12	5.10.56	-33.962	-72.132	13	4.6 TE/TN
11/11/12	5.46.48	-33.977	-72.183	16	4.8 TE/TN
11/11/12	7.24.21	-33.973	-72.272	38	4.4 TE/TN
11/15/12	20.32.37	-32.666	-71.825	23	4.7 TE
11/15/12	23.41.02	-30.988	-71.171	66	4.2 TE
11/17/12	23.51.39	-37.594	-73.825	21	4.0 TE
11/18/12	13.29.28	-38.286	-73.690	56	4.7 TE/TN
11/19/12	14.08.59	-33.969	-72.150	1	4.2 TE/TN
11/19/12	16.45.50	-33.928	-72.170	11	5.1 TE/TN
11/20/12	16.23.25	-33.921	-72.254	16	5.4 TE/TN
11/21/12	18.16.38	-33.931	-72.100	19	5.1 TE/TN
11/21/12	21.36.23	-33.939	-71.868	18	5.7 TE/TN
11/21/12	22.51.23	-34.012	-72.305	35	4.2 TE/TN
11/21/12	22.52.29	-33.916	-71.994	16	5.2 TE/TN
11/29/12	0.09.39	-32.910	-69.106	8	5.0 TE/TN
11/29/12	20.40.59	-36.426	-71.082	3	4.2 TE
12/02/12	3.29.23	-35.541	-72.766	15	4.3 TE/TN
12/04/12	9.26.14	-32.710	-71.751	38	4.6 TE/TN
12/10/12	15.25.47	-38.932	-72.862	33	4.8 TN
12/16/12	22.46.11	-33.803	-71.408	63	4.7 TE/TN
12/17/12	8.38.25	-32.342	-65.287	20	4.4 TN
12/18/12	0.45.03	-33.645	-71.187	66	3.7 TE/TN

Date, Time, Lat., Lon., Dep. and  $M_w$ , the moment magnitude, are

provided by USGS (<http://earthquake.usgs.gov/earthquakes/>). For Array ID, TE and TN indicate TE-array and TN-array, respectively.

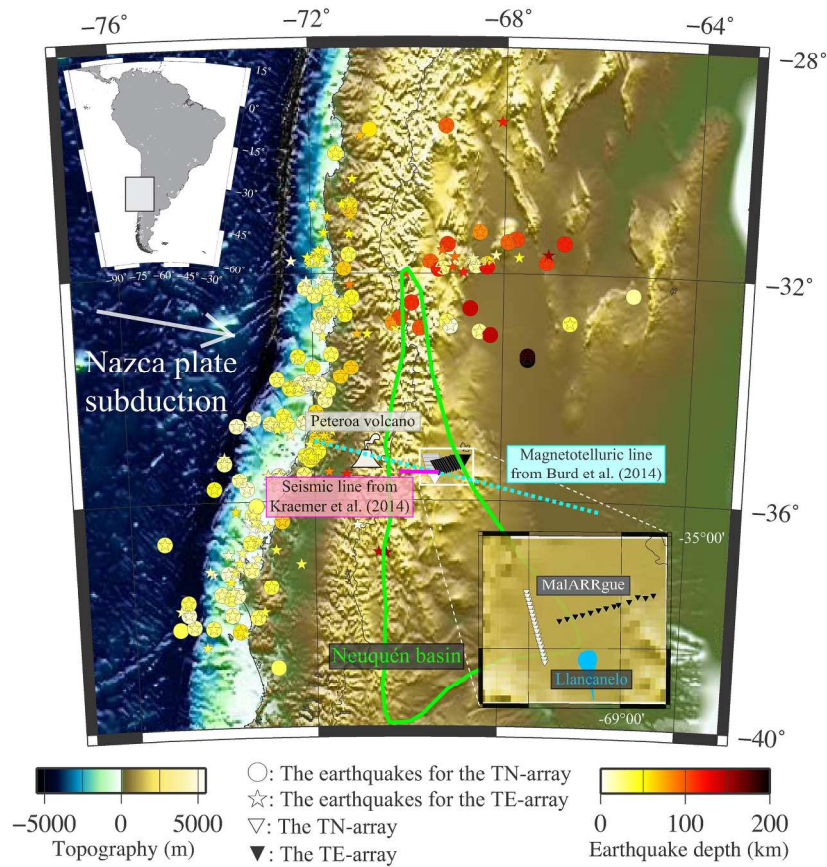


Figure 1.: Distribution map of the local earthquakes ( $2^\circ \leq$  epicentral distance  $\leq 6^\circ$ ) used in our study. The 115 circles and 210 stars show the locations of the earthquakes recorded by the TN- (the white triangles) and TE-array (black triangles) parts of the MalARRgue array; the earthquakes are color-scaled as a function of their focal depth. The volcano symbol indicates the location of the Peteroa volcano. The green outline indicates an approximated location of the Neuquén basin (derived from Mescua et al., 2013). The blue polygon indicates an approximated location of the lake Llanquanelo. The magenta solid and blue dashed lines indicate the location at which active-source seismic and an magnetotelluric sections are obtained by Kraemer et al. (2011) and Burd et al. (2014), respectively, which are discussed in Results and Interpretation of this paper.

225x259mm (300 x 300 DPI)

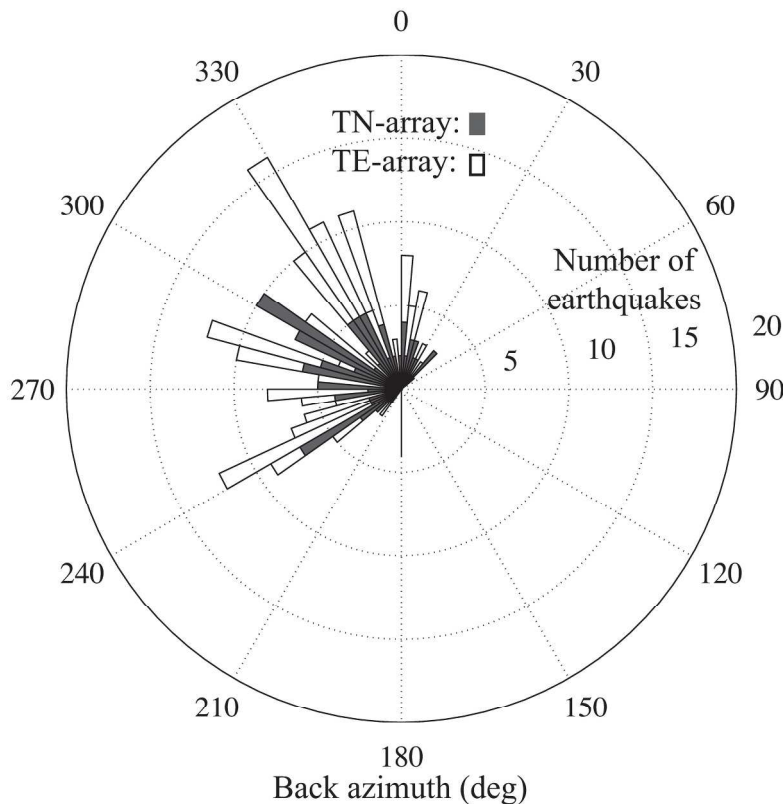


Figure 2.: Distribution of the back azimuth of the local earthquakes recorded by the TN-array and TE-array. 230x186mm (300 x 300 DPI)



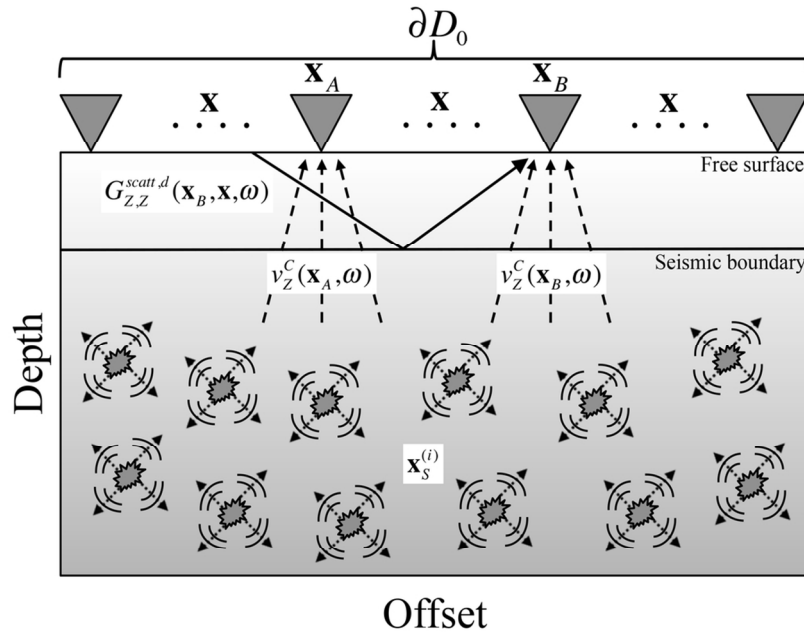


Figure 3.: A schematic illustration of equation (5).  
108x88mm (300 x 300 DPI)

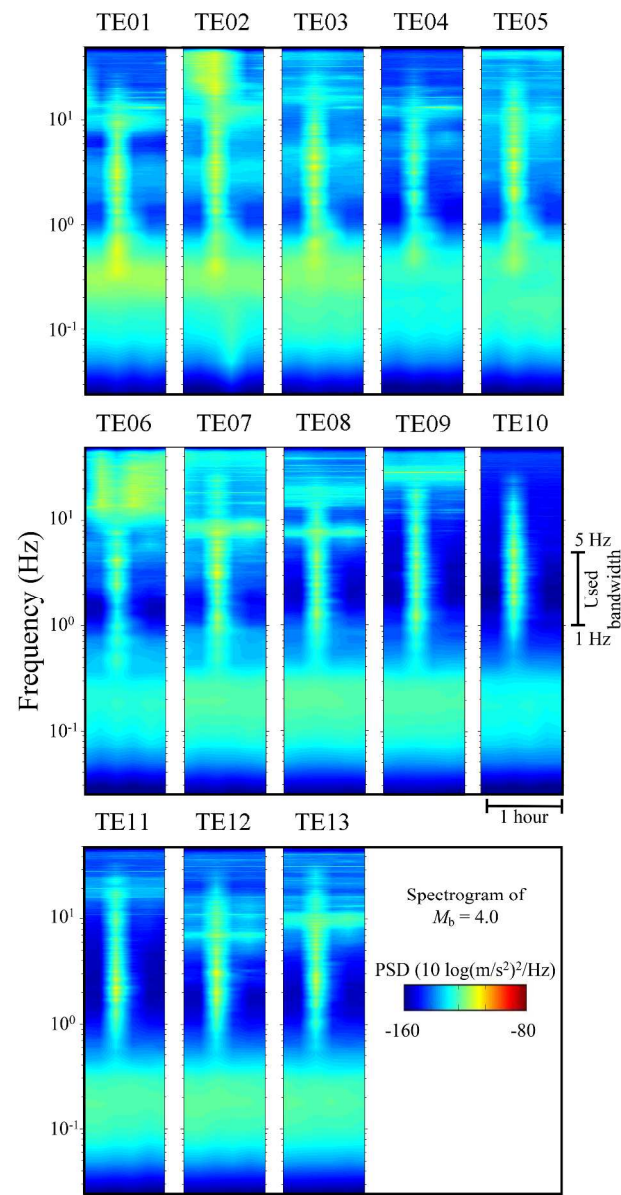


Figure 4.: Power spectral densities for a local earthquake with  $M_b = 4.0$ . The power spectral densities are computed for the TE-array.  
177x317mm (600 x 600 DPI)

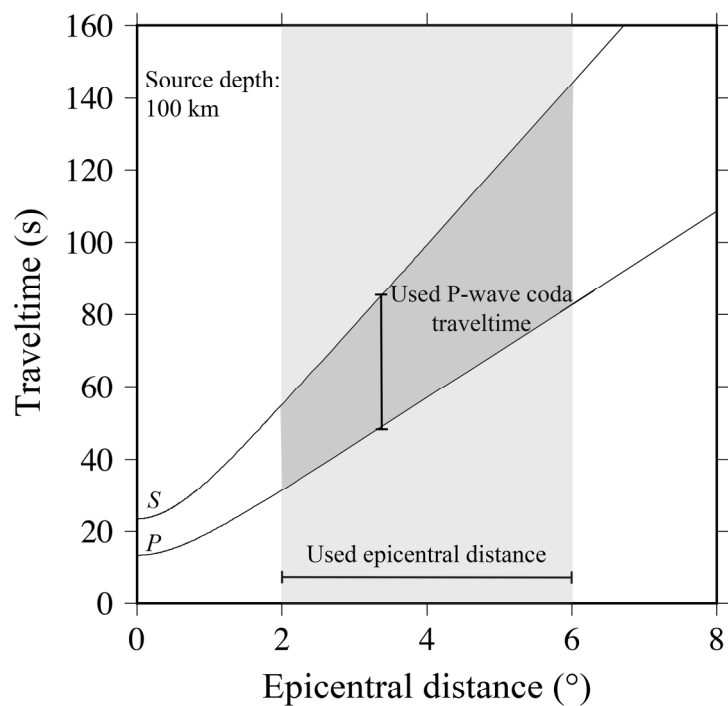


Figure 5.: Used window length of the P-wave coda as a function of epicentral distance. The traveltime curves are drawn using the regional velocity model from Fariás et al. (2010) for depths down to 110 km and the ak135 model (Kennett et al., 1995) for greater depths. Light gray rectangular indicates the used epicentral distance, while the dark gray area indicates the the window lengths to be extracted for an earthquake characterized by a source depth of 100 km.  
190x210mm (300 x 300 DPI)

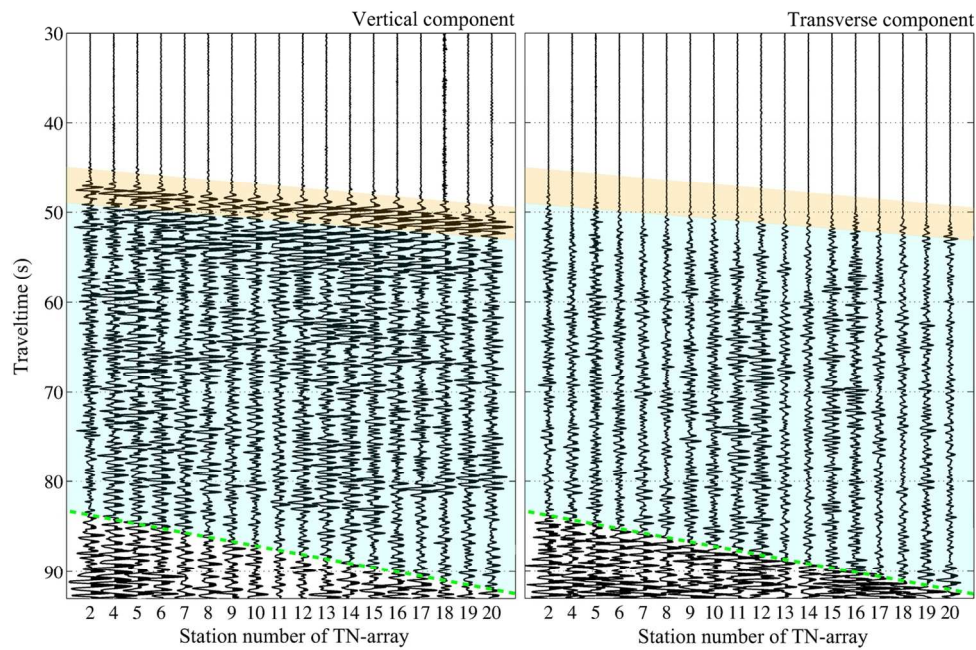


Figure 6.: An example recording of a local earthquake on the vertical (left panel) and transverse component (right panel) of the stations from the TN-array. The areas highlighted in orange indicate the direct P-wave arrival from the local earthquake, while the green lines indicates the S-wave onset. The area highlighted in light blue indicates the P-wave coda to be extracted.

130x88mm (300 x 300 DPI)

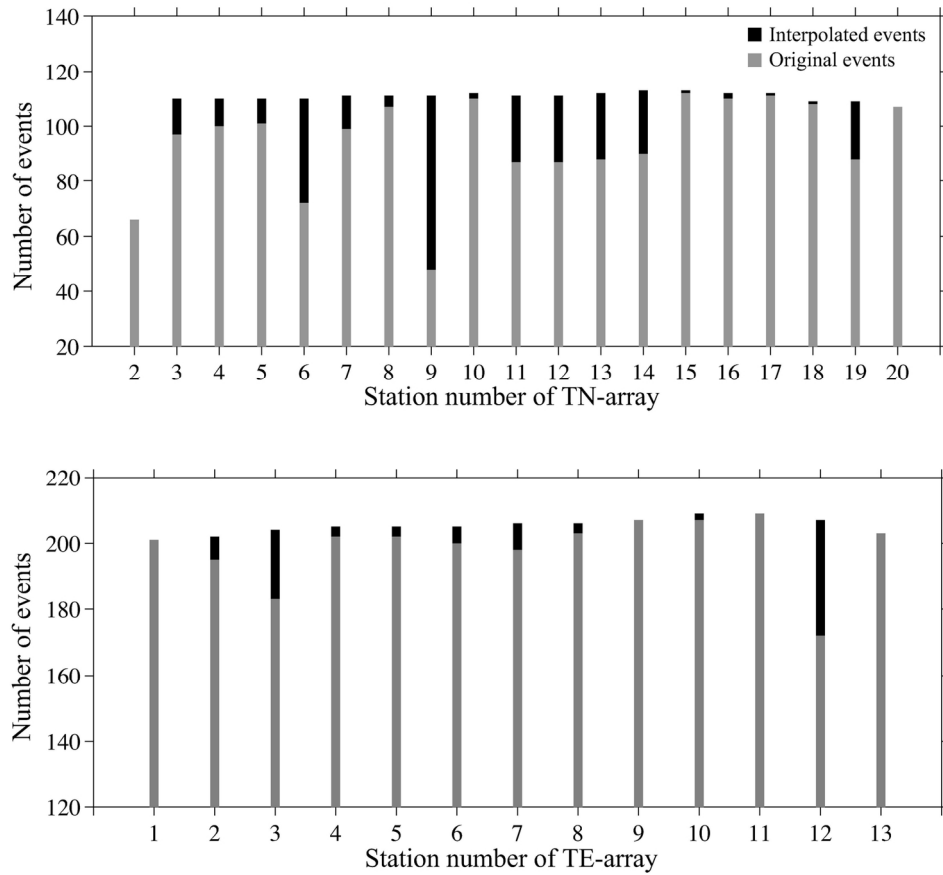


Figure 7.: Number of original and interpolated events for each of the TN- and TE-array stations.  
152x138mm (300 x 300 DPI)

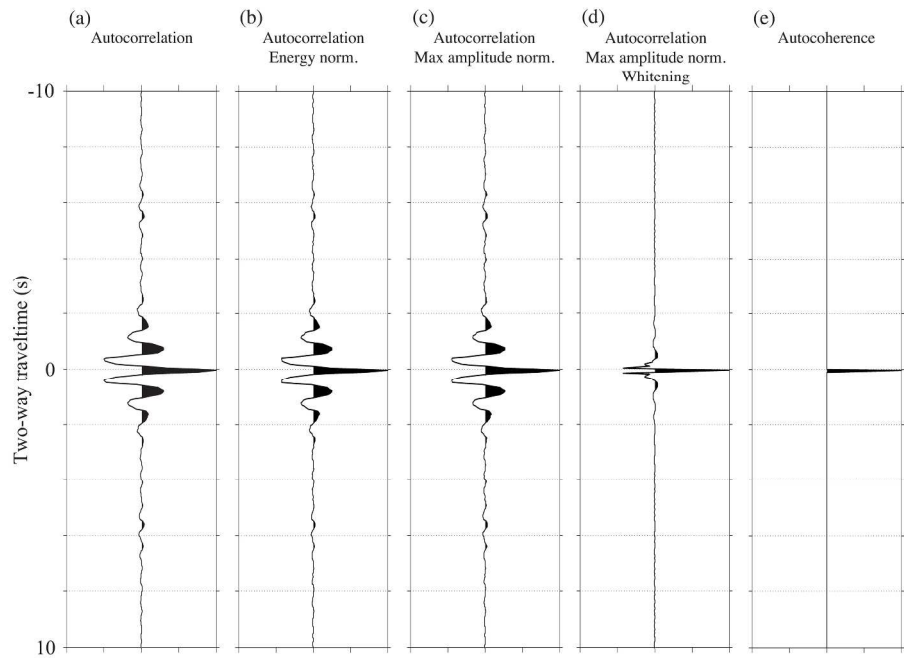


Figure 8.: Retrieved zero-offset trace at station TE07 of the TE-array obtained using (a) autocorrelation without amplitude normalization, (b) energy normalization before autocorrelation, (c) maximum-amplitude normalization before autocorrelation, (d) maximum-amplitude normalization followed by spectral whitening before autocorrelation, and (e) autocoherence.

247x174mm (300 x 300 DPI)

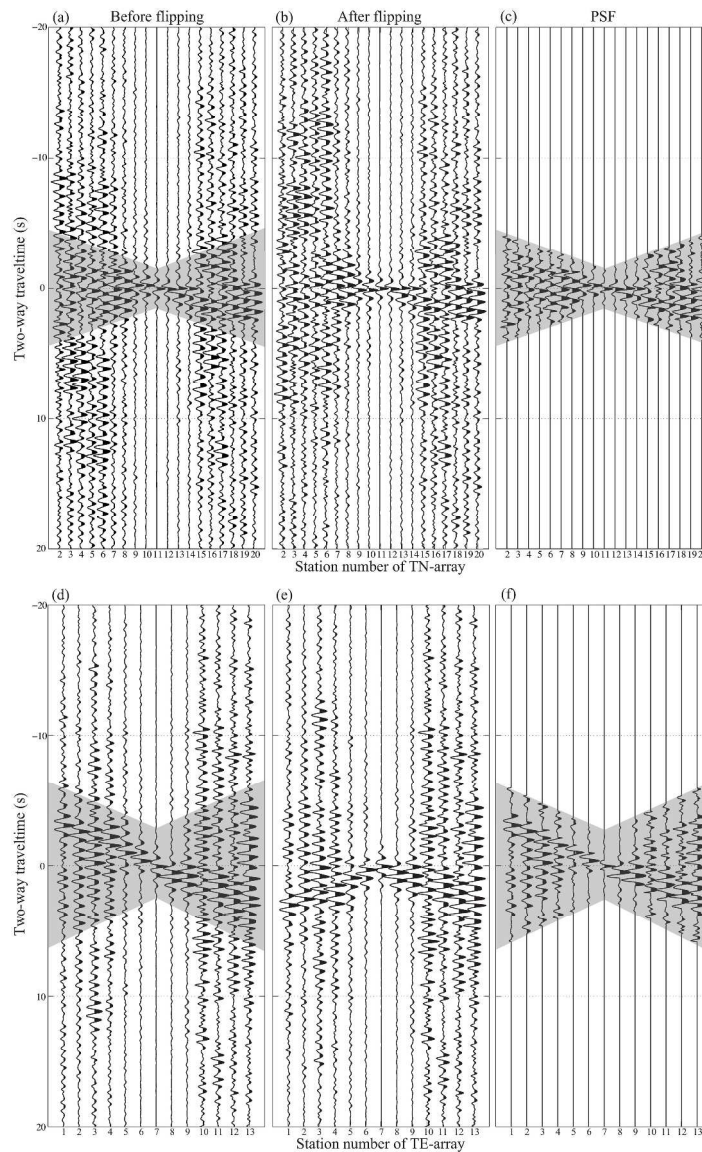


Figure 9.: Retrieved common-source gather for a virtual source at (a) station TN11 of the TN-array before flipping, (b) after flipping the negative times, (d) station TE07 of the TE-array before flipping, (e) after flipping the negative times. The PSFs of (c) and (f) are extracted from the gray shaded areas in figures (a) and (d), respectively. The results are retrieved using correlation and after summation over the used local earthquakes.

305x480mm (300 x 300 DPI)

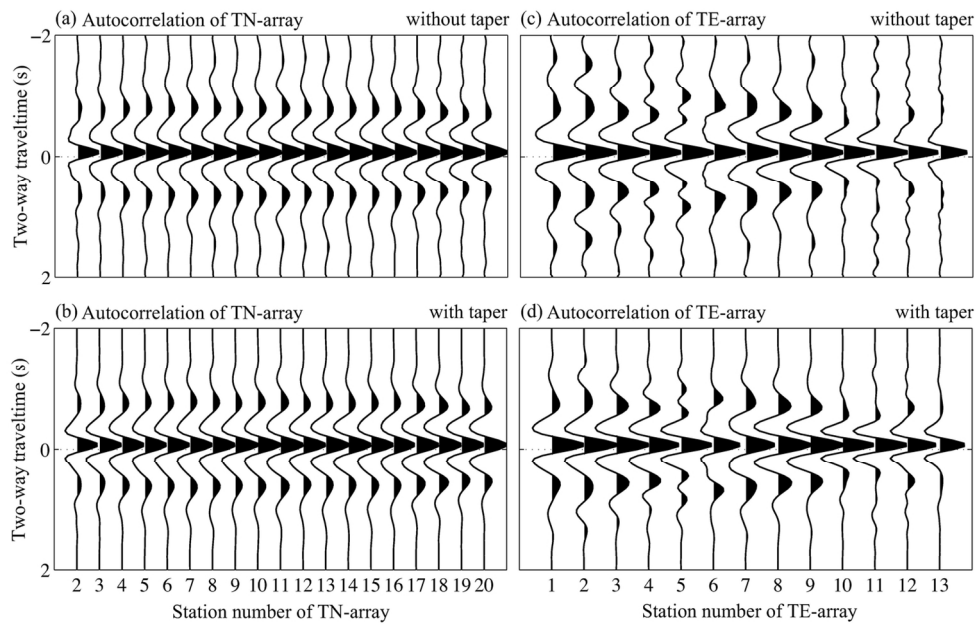


Figure 10.: Retrieved zero-offset traces using all events from (a) the TN-array (c) the TE-array. (b) and (d) are estimated source time functions from the zero-offset traces in (a) and (c), respectively, after application of time windowing.  
133x86mm (300 x 300 DPI)



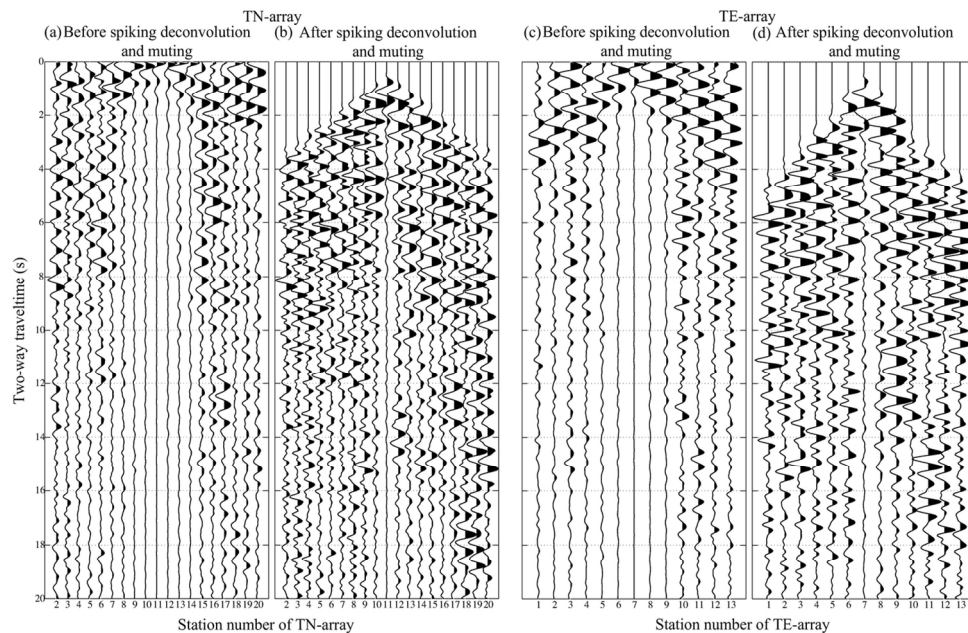


Figure 11.: A comparison of common-source gather: for station TN11 of the TN-array (a) before spiking deconvolution and muting the first breaks and (b) after spiking deconvolution and muting the first breaks and above; for station TE07 of the TE-array (c) before spiking deconvolution and muting the first breaks and (d) after spiking deconvolution and muting the first breaks and above.  
 129x84mm (300 x 300 DPI)

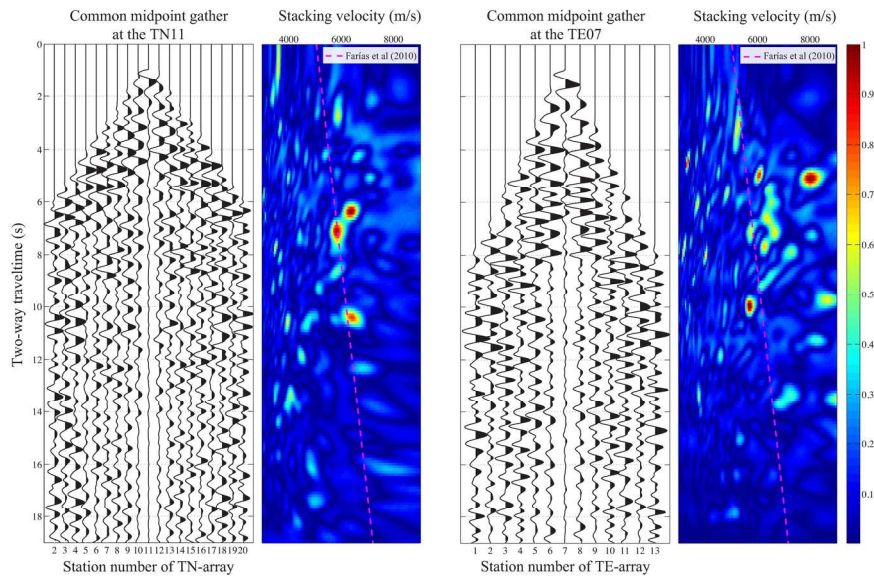


Figure 12.: Examples of velocity semblance of common midpoint gather for station TN11 of the TN-array (left panels) and station TE07 of the TE-array (right panels) with the regional velocity model of Fariás et al. (2010) denoted by the magenta dashed lines.  
190x142mm (300 x 300 DPI)

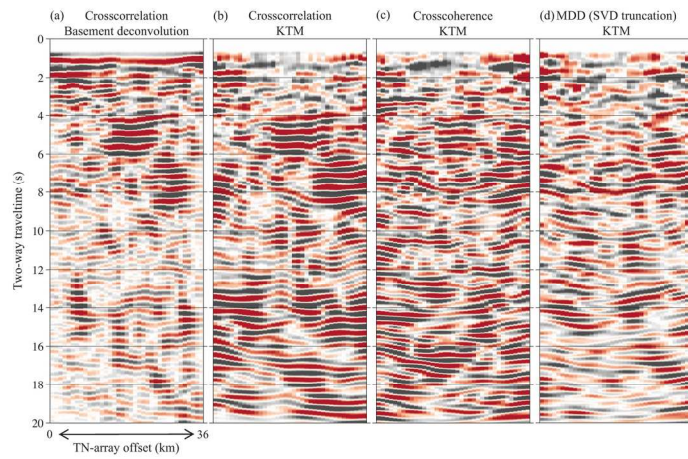


Figure 13.: A comparison of LEPC SI results for the TN-array using different SI theories: (a) crosscorrelation after basement deconvolution without KTM; (b) same as (a) but with KTM; (c) same as (b) but for crosscoherence; (d) same as (b) but for MDD using the truncated SVD scheme.  
 169x84mm (300 x 300 DPI)

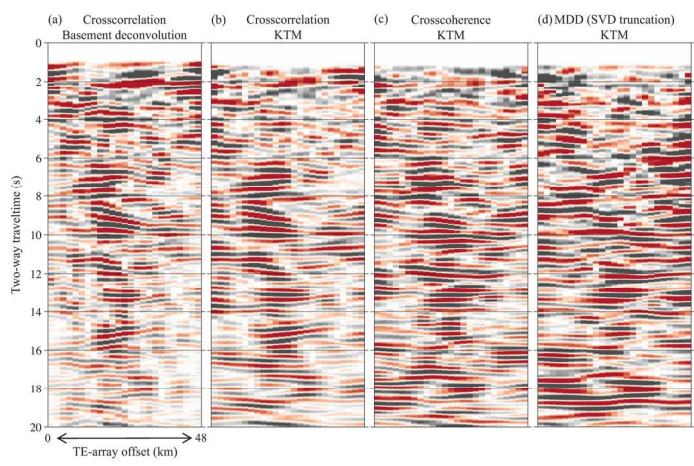


Figure 14.: Same as Figure 13 but for the TE-array.  
169x84mm (300 x 300 DPI)

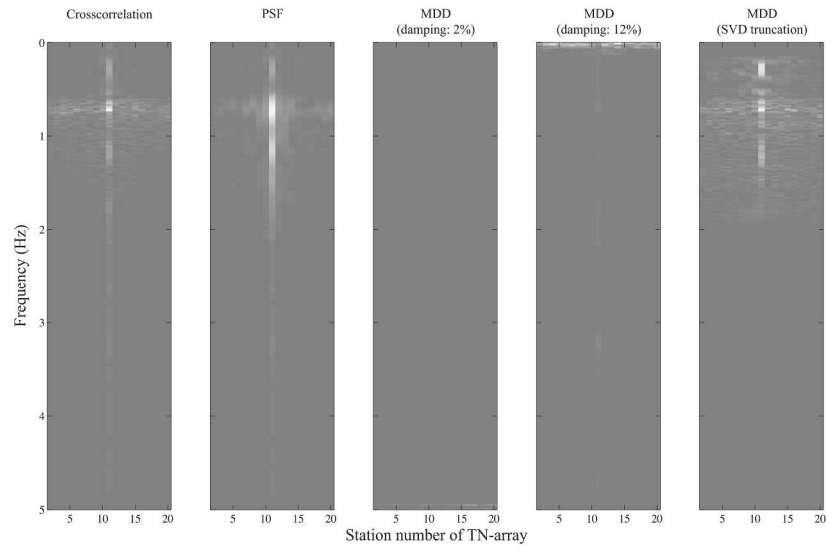


Figure 15.: Obtained MDD results using the damped least-square and the truncated SVD scheme in the f-x domain for virtual shots at: (a) station TN11; (b) station TE07 in comparison with the crosscorrelation (Figures 9a and 9d) and the PSF (Figures 9c and 9f).  
249x143mm (300 x 300 DPI)

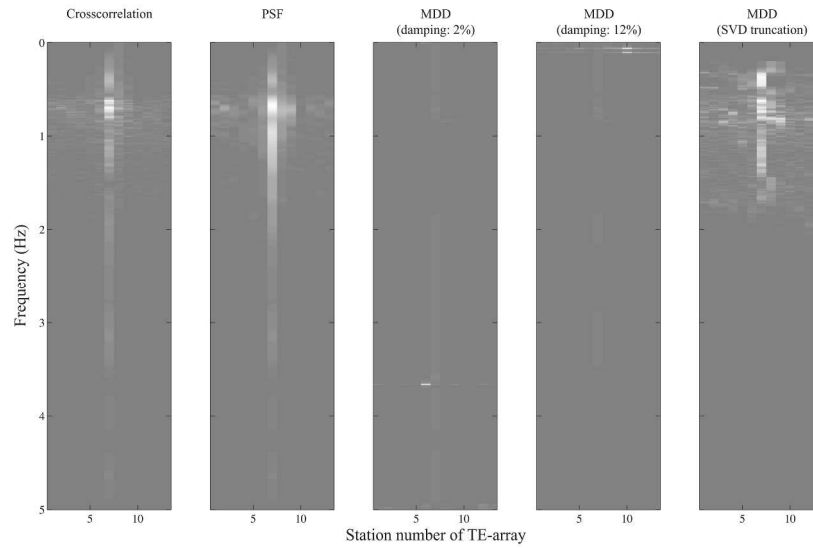


Figure 15.: Obtained MDD results using the damped least-square and the truncated SVD scheme in the f-x domain for virtual shots at: (a) station TN11; (b) station TE07 in comparison with the crosscorrelation (Figures 9a and 9d) and the PSF (Figures 9c and 9f).  
249x143mm (300 x 300 DPI)

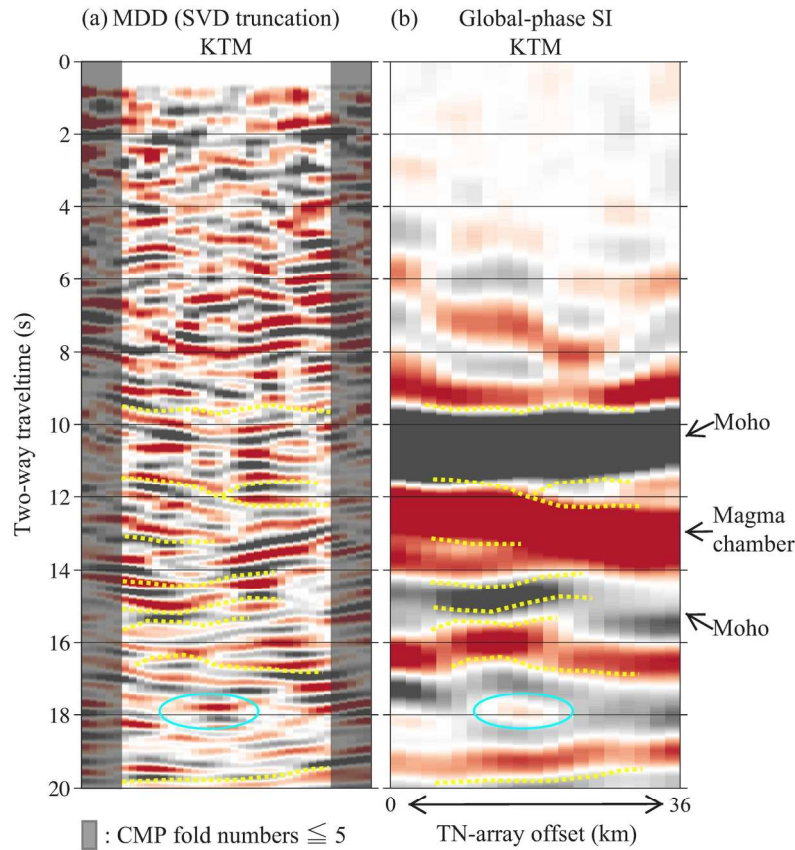


Figure 16.: Summarized interpretation on the crustal-scale reflection images beneath the TN-array obtained from: (a) LEPC SI (1-5 Hz) with the truncated MDD scheme; (b) global-phase SI (0.3-1 Hz) modified from Nishitsuji et al. (2016). The interpretation of the Moho and the magma chamber are after Gilbert et al. (2006) and Nishitsuji et al. (2016). The yellow dashed lines indicate our structural interpretation that can be traced for both the MDD and the global-phase SI results. The gray shades are the offset where the CMP folds are less than equal to 5. The cyan ellipses indicate the amplitude pockets that can be commonly interpretable between the MDD and the global-phase SI results.

167x158mm (300 x 300 DPI)

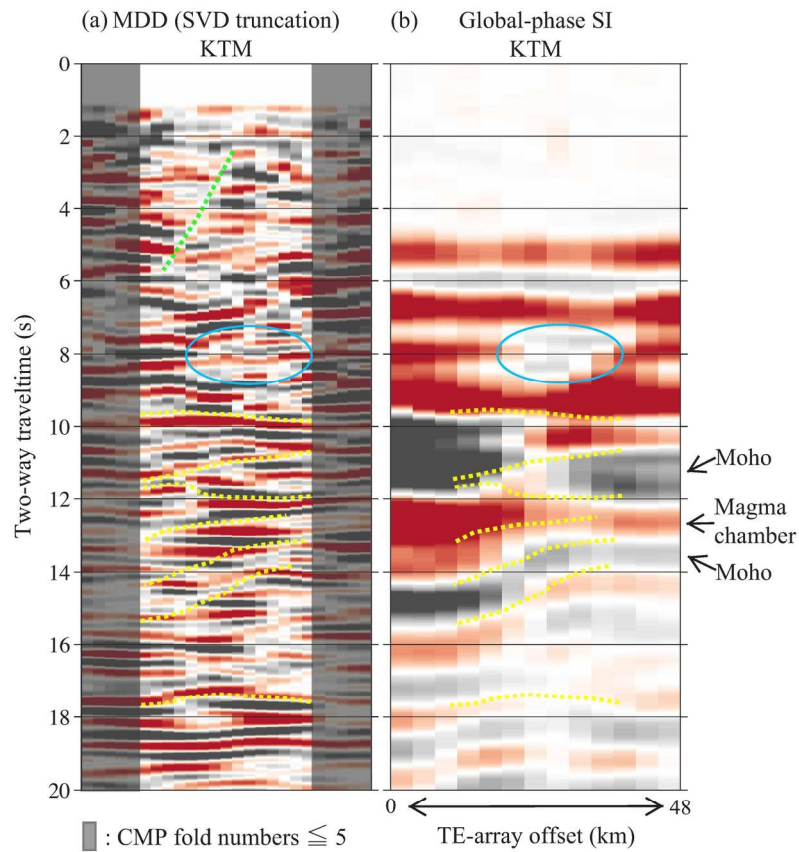


Figure 17.: Same as Figure 16, but for the TE-array. The blue ellipses indicate the dimming imaging parts that can be commonly interpretable between the MDD and the global-phase SI results. The green dashed line indicates our fault interpretation where the major deep thrust fault can be traced.  
167x158mm (300 x 300 DPI)



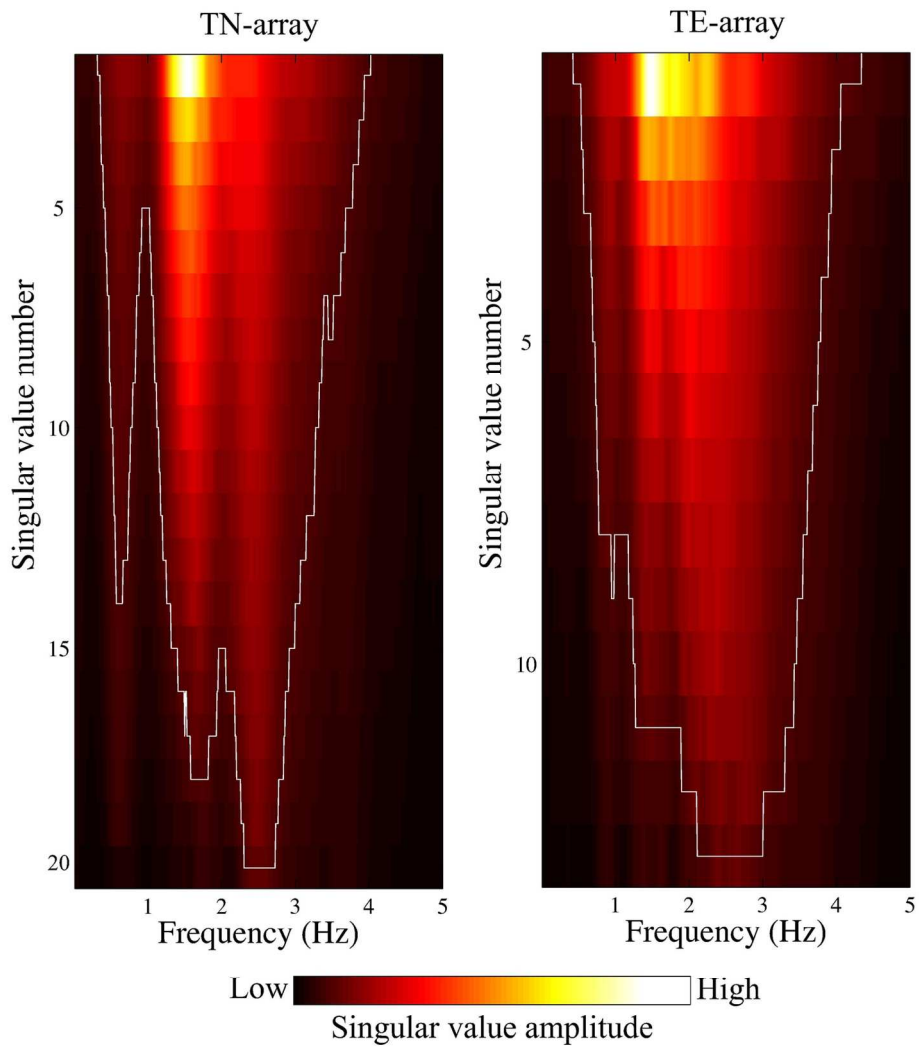


Figure B1.: Truncated singular values for the TN- and TE-array. The white lines show where 10 % of the maximum singular value lie. We truncate the lower amplitude within the white line for MDD.  
 141x156mm (300 x 300 DPI)