Ambient noise seismic reflection interferometry at the Los Humeros geothermal field, Mexico

Arie Verdel[1], Boris Boullenger[1], Joana E. Martins[1,2], Anne Obermann[3], Tania Toledo[4], and Philippe Jousset[4]

[1] Netherlands Organisation for Applied Scientific Research TNO, Utrecht, The Netherlands

[2]Department of Geoscience and Remote Sensing, Delft University of Technology, Delft, The Netherlands

[3] Swiss Seismological Service, ETH Zűrich, Zűrich, Switzerland

[4]GFZ German Research Centre for Geosciences, Potsdam, Germany

arie.verdel@tno.nl

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ABSTRACT

Integration of results from active seismic, passive seismic and well data reduces the uncertainties of several subsurface parameters that are of interest for cost-effective geothermal production operations in Los Humeros. In this study, we present results from the application of ambient noise seismic interferometry (ANSI) to retrieve zero-offset reflected P-waves from continuous seismic data recorded at the Los Humeros geothermal field, Mexico.

This study is inspired by encouraging results from the application of ANSI for body wave reflection retrieval that were reported in 2016 for a geothermal field located at Reykjanes peninsula, Iceland (Verdel *et al.*, 2016). Continuous broadband and short-period seismic recordings provided insightful reflection information that corresponded well, in relevant depth intervals, with reflectivity retrieved from the correlation of coda waves from a distant but very strong earthquake. That work was carried out within the context of EU's Seventh Framework research and innovation program IMAGE.

Encouraged by these findings, it was decided to conduct a new study following a similar approach within the context of the GEMex project, a European-Mexican collaboration. The purpose of GEMex is to gain improved understanding of geological structure and geothermal reservoir behaviour for two geothermal fields: Los Humeros and Acoculco.

In the following, we address data selection and processing aspects related to retrieval of reflected P-waves from Los Humeros seismic noise recordings. The retrieved reflections are compared with modelled reflectivities at two station locations at a close distance from the location where the seismic interval velocities that are used in the modelling were available from literature. The reflected P-wave information provides structural detail about the field at locations directly underneath the employed seismic stations.

REFLECTION RETRIEVAL FROM AMBIENT NOISE

In the past two decades, a limited but steadily growing number of publications can be found on successful retrieval of P-wave reflections from ambient seismic noise. Subsurface reflection images can provide higher structural detail as compared to velocity images from tomographic inversion of surface waves extracted from ambient noise. But the challenge to provide reflectivity information with sufficient fidelity from ambient noise is generally much larger than producing useful images from noise tomography because the retrieved body waves are orders of magnitude weaker than surface waves.

Ambient noise seismic interferometry (ANSI), used in geophysical exploration and monitoring, is known to provide valuable reflection information for the shallow crust: body-wave reflections up to depths of ~1 km were successfully retrieved with ANSI-autocorrelations by e.g. Draganov *et al.* (2007, 2009, 2013) and Boullenger *et al.* (2015). But also at much larger depths, ANSI can provide valuable reflection information: Moho-reflected P-waves (PmP) were retrieved from ANSI-crosscorrelations by Ruigrok *et al.* (2011) and Poli *et al.* (2012) and Moho-reflected S-waves were retrieved by Zhan *et al.* (2010). Autocorrelations of ambient noise for frequencies up to 0.55 Hz were used by Oren & Nowack (2017) to retrieve crustal thickness and frequencies up to 1 Hz were used by Tibuleac & von Seggern (2012) to retrieve Moho-reflected P and S from autocorrelations. Crustal thickness was mapped also by Becker & Knapmeyer-Endrun (2018) with the same technique,

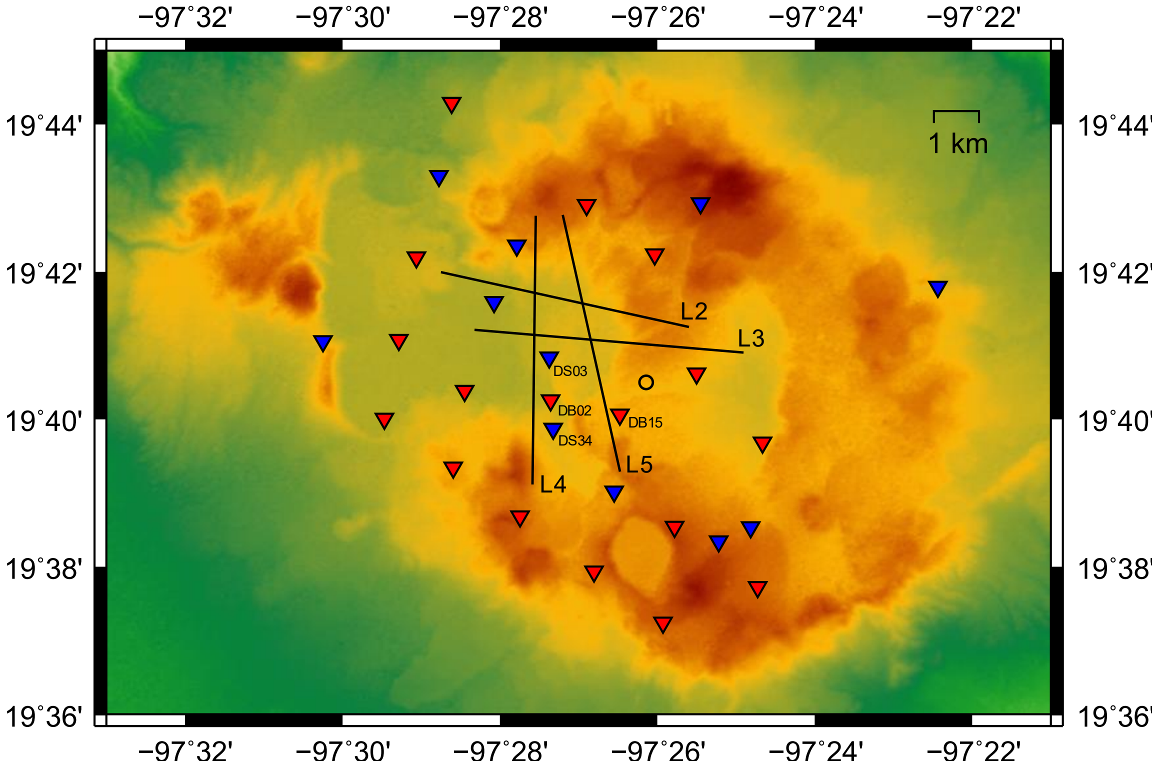

Figure 1: Topographic map of the centre part of Los Humeros showing broad band (red triangles), and short period (blue triangles) seismic station locations, the four active-source vintage seismic lines L2-L5 and the location of well H-27 (black circle).

using frequencies in the range 1.0-2.0 Hz, and more high-frequent (2.0-4.0 Hz) ambient noise was autocorrelated by Gorbatov *et al*. (2013) and Kennett *et al*. (2015) to identify PmP. The same frequency band (2.0-4.0 Hz) was used by Saygin *et al*. (2017) to determine basin-depth; their results provided indeed reflection information at shallow crustal scale. Higher frequencies, up to 8 Hz, were used by Heath et al. (2018) to determine internal volcano structure and, finally, Romero & Schimmel (2018) employed even higher frequencies than that (up to 18 Hz) to map the basement of the Ebro basin with autocorrelations from ANSI. From the here provided brief overview of ANSI examples, it can be concluded that the frequency band for which ANSI can be applied successfully for delineation of intra-crustal reflectors has broadened largely. In particular, the frequency-band has widened for ANSI-autocorrelations, and applications now range from exploration scale (up to a few km depth) at the high-frequency end to mantle scale depth at the low frequency end.

SEISMIC NETWORK AND 1D REFERENCE MODEL

Los Humeros is situated in the eastern sector of the Trans Mexican Volcanic Belt (TMVB), forming the northern boundary of the Serdán-Oriental basin. The field is a superhot geothermal system (SHGS) and is operated by the Comisión Federal de Electricidad (CFE). It is currently producing ~ 90 MW, therewith being the third most important geothermal field in Mexico. Los Humeros is geologically characterised by a caldera complex with a complicated evolution. Figure 1 shows the topographic map of the centre area of Los Humeros, the seismic station locations of the inner part of the deployed network, the locations of four old active-source seismic lines L2-L5 from the eighties and the location of well H-27 (black circle). The seismic network deployed for this study recorded continuously from September 2017 until September 2018. In the following, we will only discuss results from data recording during 2017. A 1D reference velocity model is used for comparison of modelled reflectivities with those retrieved from ambient noise. The blocky seismic velocity profile shown in Figure 2 was derived years ago using a reflection seismic profile produced by COMESA using Dix' formula in the vicinity of well H-27, see Figure 1 and also Figure 6 of Lermo (2008). This location more or less coincides with the centre of the derived seismic profile discussed in that paper. We select two seismic stations from the current network for which we describe ANSI reflectivity results: Trillium Compact broadband station DB15 and short-period Mark Sensor station DS03 (see Figure 1). Based on this selection we take an average of 2800 masl (metres above mean sea level, green line in Figure 2) for constructing an initial reference velocity model for finite-difference (FD) modelling, which is 400 m below the reference level used for the original model referred to in Lermo's 2008-paper. These two stations were selected based on position (neighborhood of active seismic lines for later comparison), seismic data availability, and a lack of instrument-related problems.

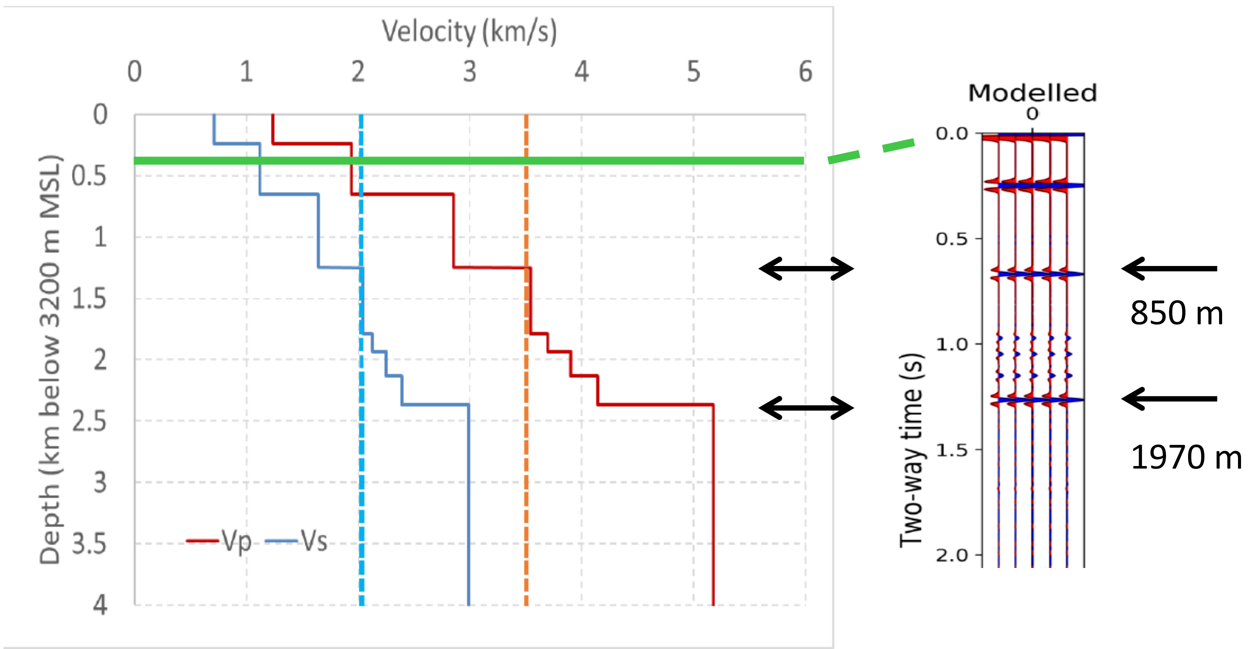

Figure 2: Left: 1D P-wave (red) and S-wave (blue) blocky velocity profiles derived from seismic data at a location close to well H-27 (see Figure 1). A constant Vp/Vs is assumed: 1.732. After Hurtado (2001) and Lermo (2001). Right: FD-modelled reflectivity trace with 15 Hz Ricker wavelet and density taken constant at 2.85 g/cm^3.

PASSIVE SEISMIC DATA ANALYSIS

In order to obtain an impression of the variability, for an arbitrary day (selected was 16 November 2017, viz. Julian day 320), of the spectral ambient noise characteristics of stations DS03 and DB15, we show in Figure 3 two 1-hour power spectral density (PSD)-displays for each station: one at 3 am local time and the other at 3pm. Clipping levels are constant per station. Notice the relatively constant 'background' noise level for frequencies below ~20 Hz. It can be clearly observed that strong short-lasting (in the order of minutes) noise bursts occur for both stations in the entire frequency band at daytime (frequencies lower than 5 Hz are tapered off).

This suggests that there are two categories of ambient noise that should be distinguished: one for frequencies lower than 20 Hz and the other for all frequencies in the studied spectral band (up to 50 Hz).

In Figure 4 we show the autocorrelation panel for station DB15, which is located at a distance of approximately 1 km from well H-27, the assumed location close to which the 1D seismic interval velocity model was derived. Each trace represents a single day-stack (the horizontal axis represents Julian days). In addition, the FD-modelled 1D reflectivity-trace for the model shown in Figure 2 is presented (modelled trace is repeated for convenience). Ideally, under perfect subsurface noise illumination conditions, each autocorrelated trace represents the global 1D zero-offset reflection response, viz. the primary reflection response plus all internal and free-surface multiples. We can see a strong variability from day to day in the stacked autocorrelations, but we fortunately also can observe continuity in the panel at various two-way-reflection times, showing up as horizontal alignments. Two strong shallow reflections are highlighted, that are taken from the modelled reflection trace, and that correspond with two large acoustic impedance contrasts that are indicated with arrows in Figure 2. Both reflections show an encouraging match for a large majority of day-stack-traces, meaning that for long periods of time (weeks to months) the autocorrelation-stacks for this station at least suggest to carry useful reflection information. The same holds true, but to a somewhat lesser extent, if we filter the data (the field data for this seismic station as well as the modelled data) in the frequency band 3-9 Hz, see Figure 5. Figures 6 and 7 show the comparable results for short-period station DS03, which is located at a distance of approximately 2 km from well H-27 (see Figure 1). We can observe similar phenomena as for station DB15, albeit that the variability of the single-day autocorrelation stacks is somewhat larger in the low-frequency band (Figure 7). On the other hand, the shallow strong reflector (highlighted in green) stands out even more clearly in the 10-40 Hz panel (Figure 6).

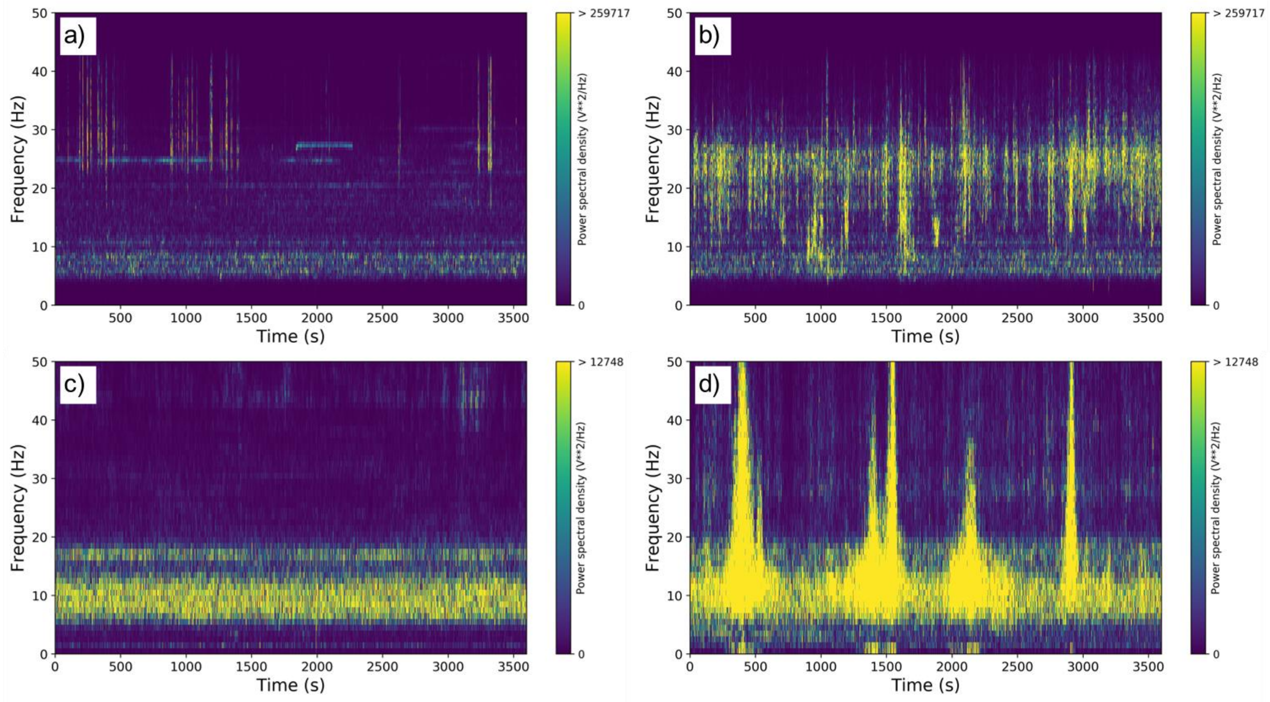

Figure 3: Power spectral density (PSD) displays showing ambient noise variability for two one-hour time windows of station a) DS03, UTC9, 3am local time, b) DS03, UTC21, 3pm local time, c) DB15, UTC9, 3am local time, and d) DB15, UTC21, 3pm local time. The clipping level per station is constant. Notice the relatively constant 'background' noise level for frequencies below ~20 Hz.

CONCLUSIONS AND RECOMMENDATIONS

We performed a simple 1D ambient noise reflection interferometry study using passive seismic data recorded during the second half of 2017 from only two selected seismic stations from the Los Humeros seismic network that was installed within the context of the combined European-Mexican project GEMex. The stations were selected based on data-availability and -quality as well as proximity to a location at which seismic interval velocity information was available from literature.

We observe clear correspondence between modelled reflectivities and single-day autocorrelation stacks produced from the field data. We consider these results as indications that passive station data contain valuable subsurface reflection information that may be used in a possible future follow-up study. In such a study, additional ANSI-processing should be performed to improve the quality of the day-stacks, such as source-wavelet deconvolution to sharpen the reflection events. Also, additional effort should be spent on 1) removal of undesired noise (bursts), 2) use of data from more stations and 3) comparison with active-seismic imaging results for lines L2-L5. Our results suggest that the locally derived 1D seismic interval velocity profile close to well H-27 in the shallow interval up to ~2 km depth, viz. up to and within the producing geothermal reservoir, can be laterally extended in the directions of DB15 (at ~1 km lateral distance) and DS03 (at ~2 km distance), which is relevant for the understanding of the geothermal reservoir that is located in the 1500–2500 metres depth range.

The ANSI auto-correlation technique applied for zero-offset reflectivity retrieval can be regarded as a promising technique, with relatively high vertical subsurface image resolution, for obtaining near-vertical velocity contrast information, corresponding with location information (depths) of near-horizontal reflectors.

As such, results from the presented passive-seismic method may partially complement and partially confirm subsurface information derived from active-seismic, that can only be acquired at a higher cost, which is more labour-intensive and which has more impact on the environment.

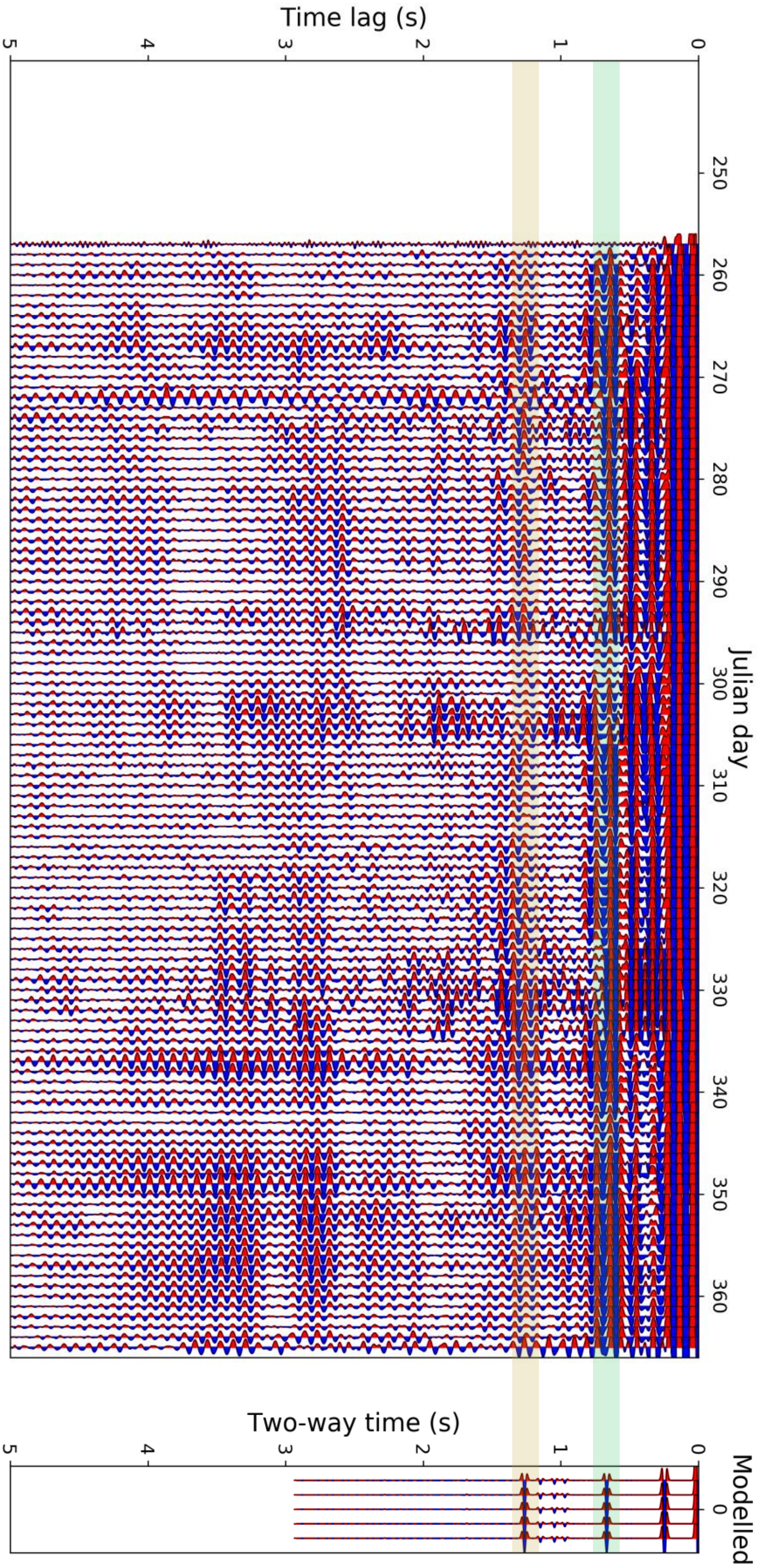

Figure 4: Panel of 10-40 Hz bandpass-filtered day-stacks of autocorrelated ambient noise (vertical component) recorded at station DB15 throughout year 2017 (from September onwards) in a combined display with FD-modelled 1D reflection response (bottom). Two key reflectors are highlighted in green and orange.

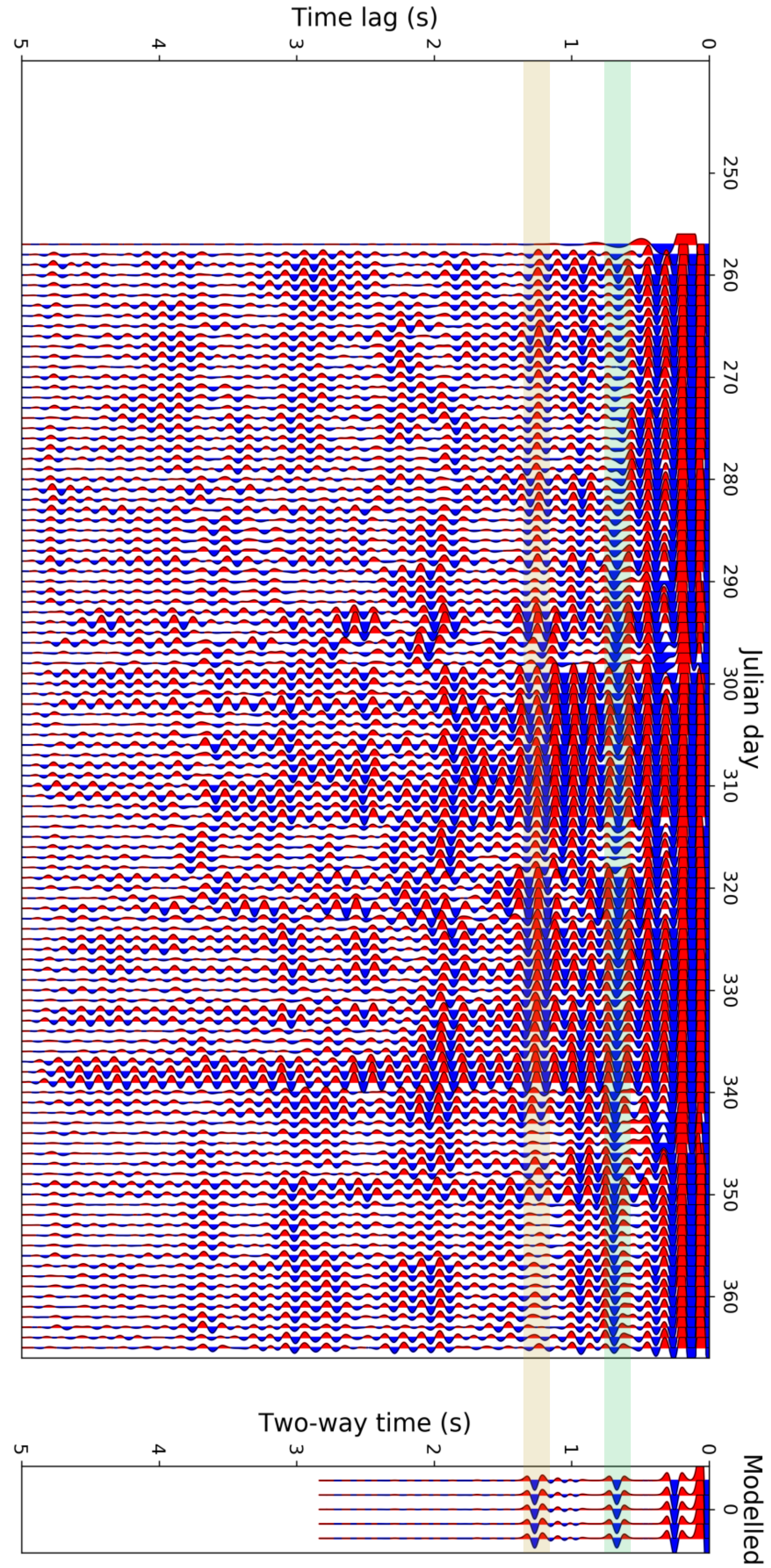

Figure 5: Panel of 3-9 Hz bandpass-filtered day-stacks of autocorrelated ambient noise (vertical component) recorded at station DB15 throughout year 2017 in a combined display with FD-modelled 1D reflection response (bottom). Two key reflectors are highlighted in green and orange.

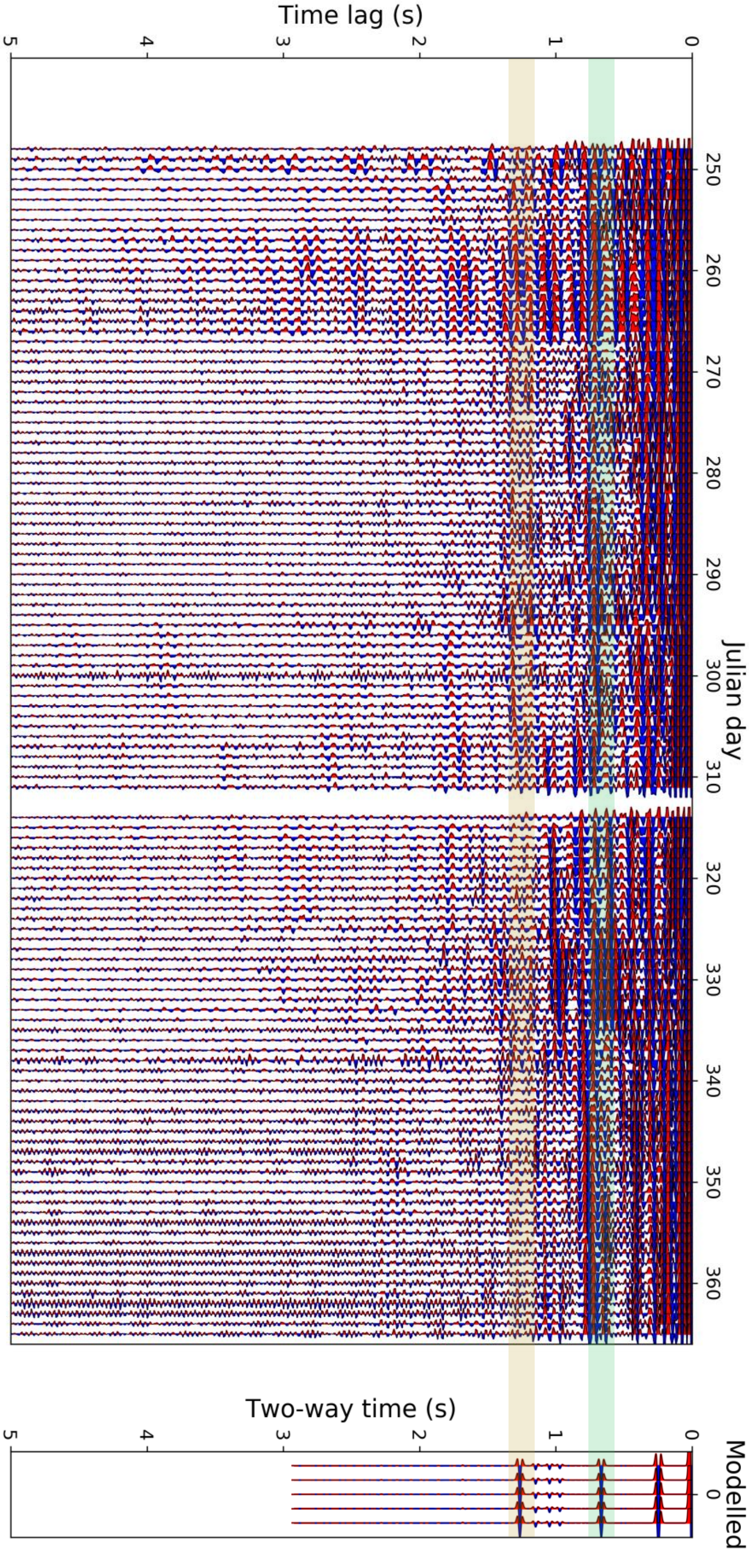

Figure 6: Panel of 10-40 Hz bandpass-filtered day-stacks of autocorrelated ambient noise (vertical component) recorded at station DS03 throughout year 2017 (from September onwards) in a combined display with FD-modelled 1D reflection response (bottom). Two key reflectors are highlighted in green and orange.

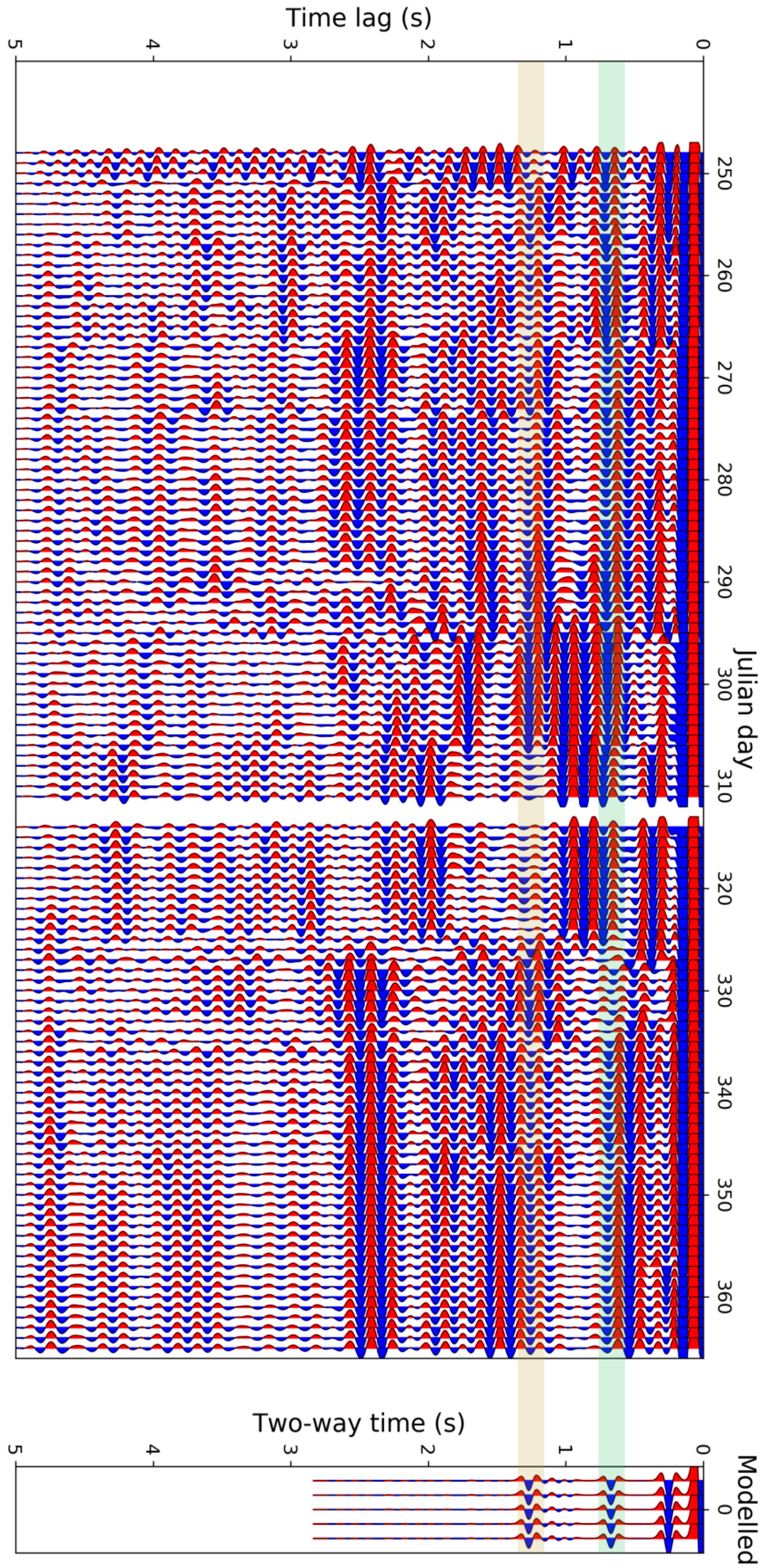

Figure 7: Panel of 3-9 Hz bandpass-filtered day-stacks of autocorrelated ambient noise (vertical component) recorded at station DS03 throughout year 2017 in a combined display with FD-modelled 1D reflection response (bottom). Two key reflectors are highlighted in green and orange.

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