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Offset-Gap Compensation by Seismic Interferometry for Shallow Signals of Active-Seismic Lines Acquired in a Superhot-Geothermal Field

E. Barison [1]*, F. Poletto [1], B. Farina [1]

[1] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Summary

We present the results of the seismic interferometry approach applied to data of four 2D legacy active-seismic lines acquired in Los Humeros superhot geothermal field (Mexico). The information about shallow waves of these dataset was limited by the large source and receiver patterns used for the acquisition, and by a 600 m central gap adopted in the shot gathers, which removes noisier traces close to the shot point.
The seismic interferometry using the illumination by real surface sources filled the gap creating virtual sources for the receivers at shorter offsets.
Thus, we got an estimation of the wavefields at shorter seismic times, i.e. very shallow layers (~100 m).
The comparison with the results of the interferometry applied to synthetic data validates the use of this method to recover shallow seismic information and confirmed the signal trends observed at shorter times in the real interferometric data.
These outcomes will be used by inversion method and joint interpretation of other geophysical, geological and well results of this area within the GEMex project.

Introduction

The Los Humeros active caldera located in the northernmost part of the eastern sector of the Trans-Mexican volcanic belt (Carrasco-Núñez et al., 2017) is one of the oldest producing geothermal fields in Mexico (Arzate et al., 2018). Imaging of the deep structures of this superhot geothermal system is one of the targets of the joint European and Mexican cooperation in the H2020 GEMex project (GEMex, 2016). Geophysical and geological studies have been done in the past to understand and characterize this geothermal reservoir with temperatures at depth reaching 300 – 400 °C (e.g., Arzate et al., 2018; Carrasco-Núñez et al., 2017; Urban and Lermo, 2013). In 1998 the Compañia Mexicana de Exploraciones S.A. (COMESA) acquired in the Los Humeros Caldera four 2D reflection seismic lines (L2, L3, L4 and L5) with Vibroseis source, for Comision General de Electricidad (CFE). The position map of this active-survey is shown in Fig. 1. OGS reprocessed these lines in the framework of GEMex project (GEMex, 2016) with the aim to extract additional seismic information on deep structures from these vintage data. At the same time, these data have been processed to obtain shallow (up to 500 – 700 m depth) information by tomographic inversion of diving waves (Böhm et al., 2019). The signal processing required significant editing and quality control to mitigate noisy data.

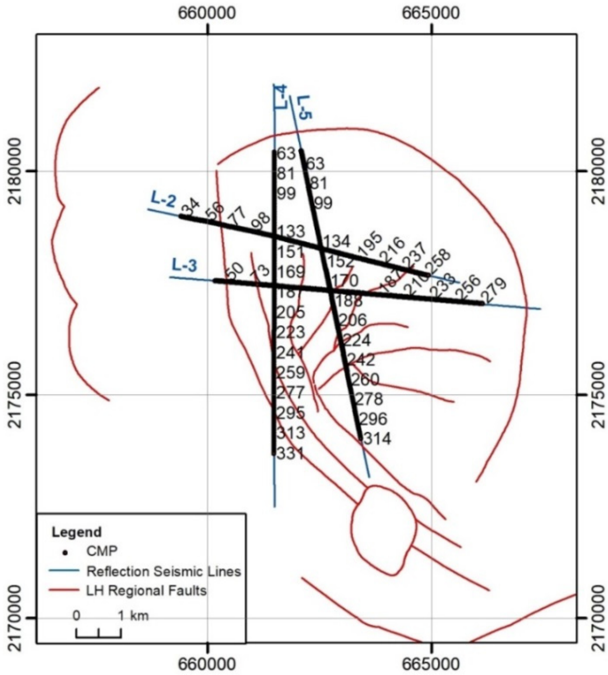

***Figure 1** Los Humeros seismic lines position map, in which CMP are evidenced. The red lines indicate interpreted faults (modified after Calcagno et al., 2018).*

Large (~100 m) source patterns and receiver arrays were used for the acquisition of these active seismic lines. Although effective in attenuating surface waves, the adopted acquisition configuration recorded noisy trace, especially at higher frequencies and positions closer to the shot point (short offsets). We observed that in the field-shot records there is a 11-traces gap (600 m = 2 × 300 m per side), which was probably adopted to remove traces with higher noise levels. However this gap limits information on the shallower layers introducing a discontinuity for the analysis of shorter offset data.
On the other hand, the task of recovering deep information at Los Humeros by active seismic and passive seismological (e.g., Verdel et al., 2019) methods involves also the issue of recovering reliable near-surface seismic information at locations where the surface measurements are taken. Thus information about shallow layers is important for the purposes of the investigations in this geothermal area. The lack of traces, due to the central offset gap, limits the information conveyed by direct and refracted waves, making it difficult to evaluate the behaviour in very shallow layers (~100 m) by direct measurements. Since the condition of continuity in space with regular spacing is available at the surface for the receiver traces, we adopted the alternative solution to use the seismic interferometry approach by the active seismic data. In this way we

create virtual sources for other receivers, also those at shorter offsets, conversely missing in the original data. Here, we present the results obtained by applying seismic interferometry both using real and synthetic seismic dataset for lines L2 - L5.

Shallow seismic interferometry approach

The seismic interferometry method is well known in seismic literature. Among others, we may cite the original concept by Bakulin and Calvert (2006), Wapenaar et al. (2008), and also supervirtual resolution variants (e.g., Schuster, 2009). We refer to the shallow virtual source model shown in Fig. 2a, where we use direct, and shallow turning diving waves to obtain virtual sources (VS) by receivers illuminated by the real sources S_i. These shallow signals have typically large incidence and emergence angles, and are significantly low-pass filtered by source and receiver patterns frequency responses (Fig. 2b) (calculated using parameters of COMESA, 1998), depending on emergence and incidence angles and local velocities (Böhm et al., 2019). Considering causal contributions in the signal correlations, let x_{VS} and and x_R be signals recorded at receivers at the virtual source position and generic receiver at left side position with respect to the source, respectively, and let S_i be sources at the right side. We obtain the left-side virtual source signals by

$$x_{R,VS}^{-} = \sum_{Si>VS} x_R x_{VS}^{*}, \qquad [1]$$

where the signals are represented in the Fourier frequency domain and '*' denotes complex conjugation. The time signals are obtained by inverse Fourier transforming equation 1. Note that equation 1 is calculated by summing the signals obtained with sources at positions $S_i > VS$. Limitations can be introduced to avoid shorter and noisier offset traces. As schematically represented by the horizontal-bold arrow in Fig. 2, this procedure provides an estimate of the Green's function from VS to R, as an approximation depending on the nature of the illuminating waves. A similar calculation can be performed to obtain the right virtual signals $x_{R,VS}^{+}$ using energizations at the left side with respect to the VS position. We process the data from both the sides using causal and anti-causal signals, which are summed together in the results after time reversing the anti-causal parts. Gating traces to select in time the events in the reference used for correlation traces is also beneficial. Combining the left side and right side contributions we obtain the virtual traces of a split-offset shot gather, thus also the traces required to fill the offset gap around the real source.

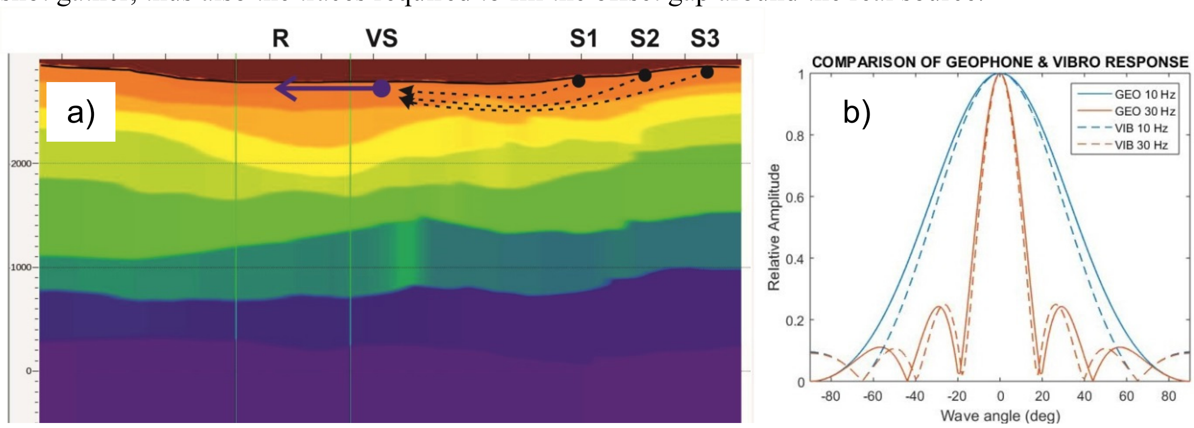

Figure 2 a) *Seismic interferometry using active seismic data. A virtual source (VS) is created for a receiver R using the sources S_i. b) Comparison of vibrators and geophone array responses versus emission and incidence angles, at different frequencies, assuming formation velocity 2000 m/s.*

Real and synthetic examples

The evaluation of the asymptotic approximation in the interferometric reconstruction of direct arrivals is matter of further analysis of this dataset. For this purpose, we use also full-waveform elastic synthetic signals calculated for the seismic lines to verify the interferometry wavefields: i.e., those used to fill the gap section. To calculate the synthetic data, we use a 2D P-SV finite-difference code (modified after Levander, 1988), with a discretization grid of 10 m. This discretization makes it possible to reconstruct only partially the directional attenuation effects of recording patterns, which are important in the real data. The depth velocity model used to calculate the synthetic data comes from the velocity analysis performed during the depth processing of the reflection seismic data, refined with Common Image Gather (CIG) analysis and model interpretation.

Figure 3 shows examples of a) real shot data (of L5) with the offset gap, and b) the merged gather filled with virtual-souce signals. The signals are filtered in the low-frequency bandwidth to remove shallow high-frequency noise, and boost the continuity in the signals attenuated by the field acquisition patterns. Figure 4 shows a) the complete synthetic shot, where the gap zone is evidence by a red-dashed box, and b) the merged synthetic shot with the offset gap filled by interferometry traces. Althogh with a different signal content, that would require further trace merging to reproduce the strong recording pattern effects, the synthetic results confirm the results and trends observed in the real data of Fig. 3, where the gap traces are not available in the original field data. These data will be used to fill very shallow signals for tomographic inversion as discussed in Böhm et al. (2019), with interpretation of direct and shallow reflection arrivals, thus improving the local near-surface information (in the first ~100 m) useful for shallow geological evaluation and deep imaging of this geothermal reservoir.

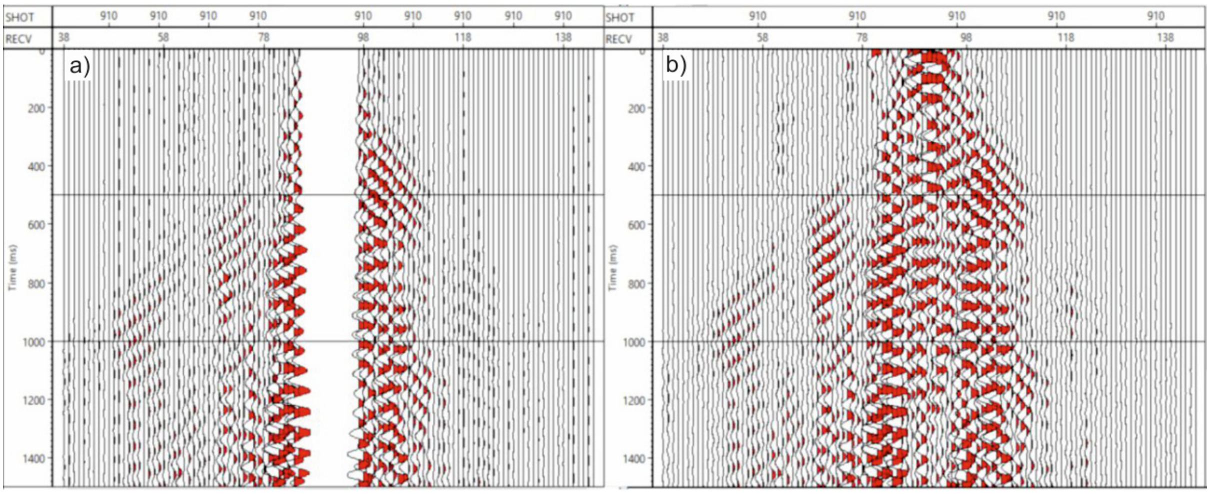

Figure 3 *On the left side, real shot of L5 with the acquisition gap between near-offset traces. On the right side, the offset gap is filled by the interferometry traces obtained calculating virtual sources with the real data.*

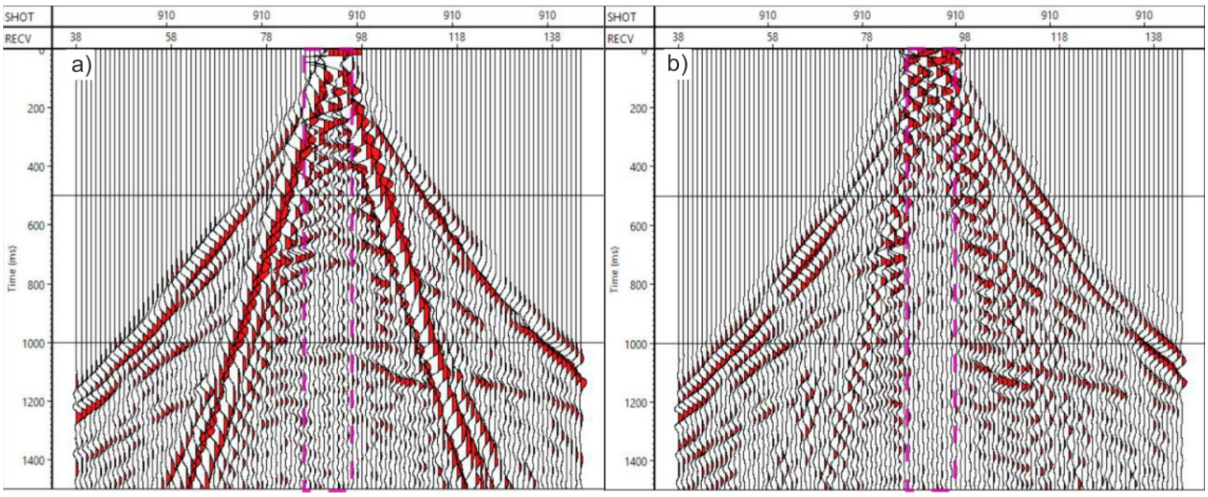

Figure 4 *Seismic interferometry on L5 synthetic signals corresponding to the real data of Fig. 3. a) Full shot and b) shot with the offset gap filled by interferometry traces.*

Conclusions

We analyze legacy data of a superhot geothermal system in Mexico, using seismic interferometry to create virtual sources in zones with acquisition gaps. Using real surface sources and receivers to create virtual sources at the surface in the gap region, this method provides estimation of wavefields at shorter seismic times, and low seismic frequency for the signals filtered by the acquisition pattern responses. Interpretation of synthetic results calculated with the model of the deeper active-seismic data processing confirms the signal trends observed at shorter times in the real data. Further utilization of these results is foreseen by inversion method and joint interpretation of other geophysical, geological and well results of this area in the framework of the GEMex project (GEMex, 2016).

Acknowledgements
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550. We thank CFE for the permission to use the legacy active-seismic data, and UNAM for providing the active-seismic data.

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