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Near-Surface Geophysical Investigation for Characterization of a Volcanic Geothermal Reservoir by Active-Seismic-Data Tomography and Attenuation

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Summary

In this work we present a geophysical analysis of the near-surface data of four active-seismic 2D lines, with the aim to characterize the deeper geothermal reservoir present in the investigated area of Los Humeros (Mexico). We obtained a detailed shallow velocity model in depth from the travel time tomography of the first arrivals computed on all the seismic lines. Using the same data, we also applied the attenuation tomography to define the map of attenuation (Q factor) in the same area. Furthermore, we used both tomographic results to evaluate possible directional and anisotropy effects at the crossing-line positions, and interpret the results in relation to the presence of a fault zone. This analysis, which extends to indicatively 500 – 700 m depth, will be used to improve the deeper imaging of the superhot geothermal reservoir.

Introduction

Los Humeros is the largest active caldera located in the northernmost part of the eastern sector of the Trans-Mexican volcanic belt (Carrasco-Núñez et al., 2017), and one of the oldest producing geothermal fields in Mexico (Arzate et al., 2018). Several studies have been done to understand and characterize from geophysical and geological point of view this superhot 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). Imaging of the deep structures of this geothermal system is one of the targets of the joint European and Mexican cooperation in the H2020 GEMex project (GEMex, 2016). This project focus on resource assessment at two unconventional geothermal sites in Mexico, and reservoir characterization using techniques and approaches developed at conventional geothermal sites. This activity includes novel geophysical and geological methods to be tested and refined for their application at the project sites, with use of passive seismic data to apply ambient noise correlation methods, and investigate anisotropy by coupling surface and volume waves; moreover electromagnetic and gravity data will be used for joint inversion with the seismic data.

For a reliable imaging of the deep structures by surface observations in complex areas as those of the volcanic system, the knowledge of the near-surface conditions is of great importance: To provide information on the local shallow model and corrections for the processing of the deeper images, and to better understand and constraint the local interpretations, which are projected to the surface and include the near surface zones (e.g., Verdel et al., 2019). In this paper we present the analysis on the near-surface seismic properties of the local geophysical model of Los Humeros, in the local area as defined by Calcagno et al. (2018). Results are obtained by processing legacy active seismic data provided by Mexican partners (courtesy of CFE and UNAM for data retrieval). These data consist of four legacy seismic lines (named L2, L3, L4 and L5), which have been reprocessed by OGS for imaging the deep structure. Using the same dataset we analysed the shallow arrivals by tomographic approach using the picking of the first arrivals. In this analysis, we use the diving-wave tomography method, which provides the P-velocity in the shallower layers, and invert the data also for attenuation (Q-factor tomography), taking into account the influence of source radiation pattern and receiver array response. The results are used for an initial interpretation of anisotropy effects in the faulted area.

Travel-time (velocity) tomography

Travel time tomography of the first breaks was computed on the active seismic data. For all the shot gathers of each line (L2 – L5) the first arrivals were picked and separately inverted for each line by using the diving ray paths (turning ray tomography) (Stefani, 1995; e.g., Böhm and Petronio 2003). For inversion, we used OGS Cat3D software. In general the quality of the first arrival in these reprocessed shallow seismic data was of variable quality, and trace editing and QC selection in the field shots was necessary. With this approach, we obtained the corresponding 2D shallow velocity models in depth. To enhance the resolution of the tomographic model, staggered grid method was used in the inversion procedure (Vesnaver and Böhm, 2000). Figure 1 shows the 3D view of the four 2D-lines results. These velocity fields provide information in the shallower 500-700 m depth, and were used to perform the static corrections that were applied to the seismic data for computing the corresponding stack sections in the initial time-processing phases.

Phase-shift (attenuation) tomography

We investigate the attenuation in the diving waves, by analysing signal wavelets selected in the shallow arrivals used for travel-time inversion. A shortcoming with respect to the attenuation inversion with seismic reflection data, is that the source emission and receiver angles are not negligible in the large-offset traces, and significant frequency-dependent directional effects due to the ~100-m patterns of sources and receivers affect the data. These can cause distortions in the attenuation analysis. For this reason, the source patterns and receiver array responses were calculated using the emergence and incidence angles and average local velocities at sources and receivers obtained by tomographic inversion of first arrivals. We compensate these responses, after adding a

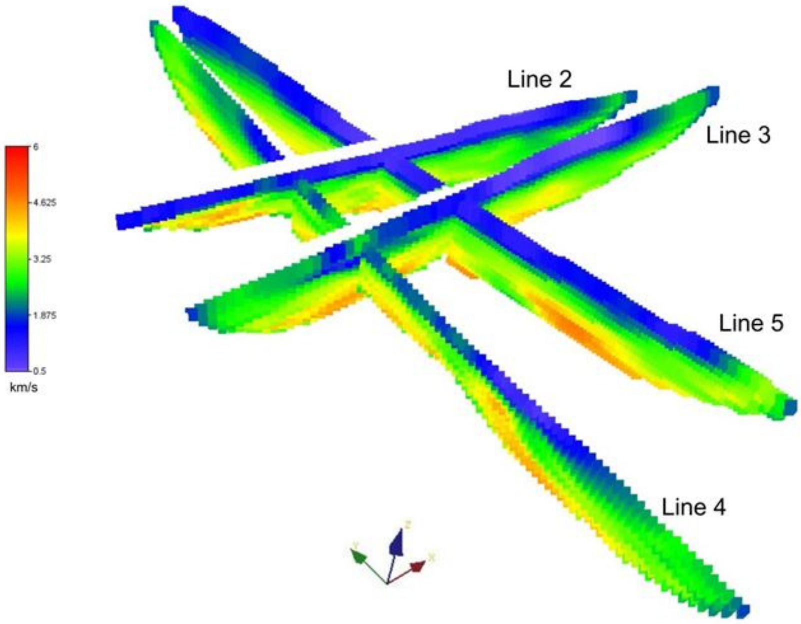

__Figure 1__ 3D view of the tomographic inversion for P-velocity of the Los Humeros seismic lines. The velocity is obtained by tomographic inversion of first arrivals picked along the profiles. The maximum depth of investigation is of the order of 500 – 700 m.

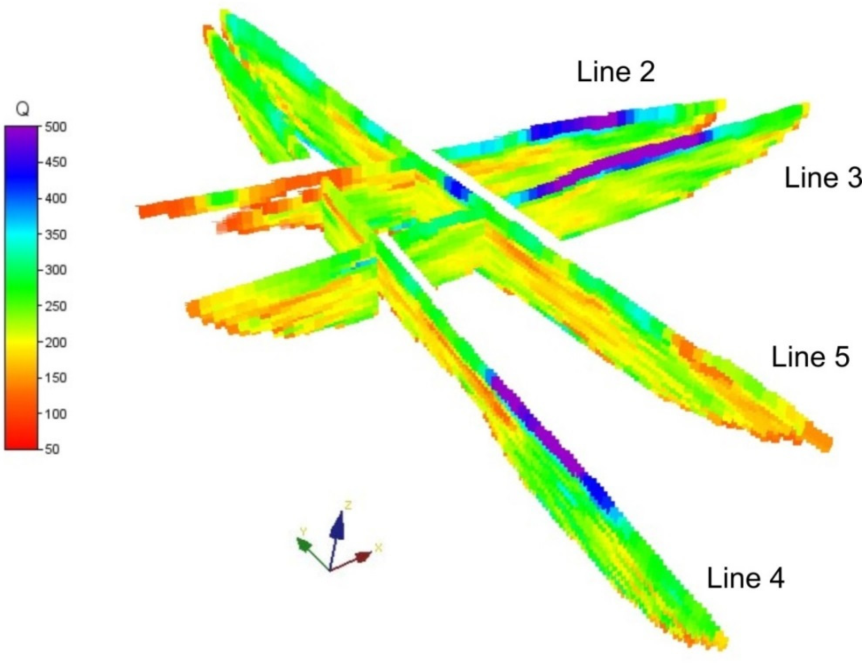

__Figure 2__ 3D view of the tomographic inversion for attenuation of the Los Humeros seismic lines.

bias in frequency to stabilize the compensation, before attenuation inversion. Then we perform attenuation tomography to obtain the distribution of Q (quality factor) in the shallow model, and attenuation by Q^{-1}. The basic approach utilized to invert for the quality factor Q is based on the frequency-shift method proposed by Quan and Harris (1997). As the wave propagates the amplitude decreases, pulse broadening occurs and high frequencies are lost.

According to this approach, a measure of the frequency shift of the spectrum in the diving wave propagated at distance x by attenuation $e^{-\alpha x}$ is the variation of the spectral content of the pulse, defined as

$$\xi = \frac{f_s - f_r}{\sigma_s^2}, \quad [1]$$

where f_s and f_r are the centroid frequencies at the source and receiver, respectively, and σ_s^2 is the spectral variance of the initial pulse. A relation similar to that used in the travel-time tomography can be established between the spectral content and the attenuation factor α, i.e.,

$$\xi = \int_{x_s}^{x_r} \alpha \, ds, \quad [2]$$

where x_s and x_r are the position of source and receiver, respectively, and assuming frequency-independent $Q = Q(x)$, we have

$$\alpha = \frac{\pi f}{vQ}, \quad [3]$$

and $v = v(x)$ is the velocity input from the velocity inversion. Figure 2 shows the shallow attenuation profiles obtained for lines from L2 to L5. As pointed out by Quan and Harris (1997), the value obtained by this estimation is relative, and some calibration would be beneficial. So we interpret the minimum value in the scale of Fig. 2, $Q = 50$, not as an absolute value, but rather as relative to its spatial distribution. As a preliminary conclusion, further analysis and data comparison is required to calibrate the magnitude of these attenuation results.

Preliminary analysis of shallow anisotropy effects

Using both velocity and attenuation results in 3D (Figs. 1 and 2), we evaluate possible directional and anisotropy effects at the crossing-line positions. The 2D lines L2, L3 and L4, L5 are, in fact, oriented in different, sub-orthogonal, directions. We compare the diving velocity models at the crossing positions of the 3D data: namely of L4 with L2 and L3, and L5 with L2 and L3. In Fig. 3a we observe differences for the velocity at the intersection of L4 with L3, where the ground surface elevation is 2.8 km. These differences in the velocity models are interpreted as possibly due to local anisotropy effects or to inhomogeneity, or presence of intersecting fault patterns. Figure 3b shows the map of the lines where the intersection between L4 and L3 is evidenced by a small blue circle, together with the geological faults interpretation (modified after Calcagno et al., 2018), with the strike according with L4 orientation. Similar results, obtained with attenuation data, are discussed in this work.

Conclusions

We present the initial velocity and attenuation results from tomographic analysis of shallow diving waves in the Los Humeros active seismic data. This preliminary analysis of shallow seismic properties extends to indicatively 500 – 700 m depth, and can be considered to improve the deeper imaging of this superhot geothermal reservoir (GEMex, 2016), integrated with additional shallow surface information, as from passive methods (e.g., Verdel et al., 2019), including geological interpretation of faults and their orientation relative to the seismic lines (Calcagno et al., 2018). These 2D results mapped along the line profiles, can be interpolated in 3D for joint geophysical applications.

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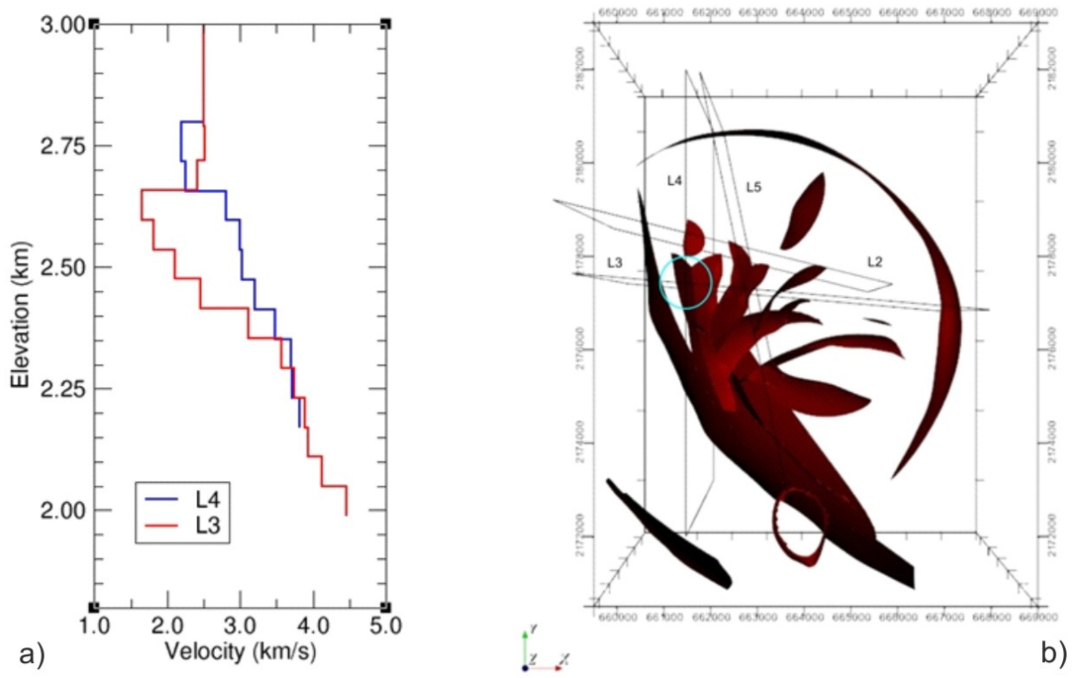

***Figure 3** a) Comparison of P-velocity profiles at the cross between sub-perpendicular L4 and L3 evidences different velocities with possible anisotropy. This zone is characterized by the presence of a shallow fault as shown by the small blue circle in (b) (modified after Calcagno et al., 2018).*

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