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Local Earthquake Tomography at the Los Humeros Geothermal Field in Mexico

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ABSTRACT

Los Humeros is a volcanic complex located at the eastern edge of the Trans Mexican Volcanic Belt (TMVB) forming the northern boundary of the Serdán-Oriental basin. It hosts one of Mexico's main geothermal fields, which is operated by the Federal Electric Comission (CFE, by its Spanish acronym). The shallow subsurface has been studied extensively, but knowledge of the geothermal system at depths greater than ~2.4 km is still rather sparse. For this reason, in the framework of the European H2020 and Mexican CONACyT-SENER project GEMex, several geophysical, geological, and geochemical surveys have been carried out to better understand the structure and behavior of the geothermal reservoir, and to investigate future development areas.

Between September 2017 and September 2018, a seismic network consisting of 23 broadband and 20 short period stations, was deployed to monitor and study the currently exploited Los Humeros geothermal field. In this study, we analyzed the continuous seismic records and applied a recursive STA-LTA algorithm to detect local micro-seismic events mainly associated with exploitation activities and local tectonics. Manual review and picking led to the location of around 500 local events, mainly clustered in three regions. Focal depths range predominantly between 1 and 4 km, which corresponds to the known reservoir interval. The extracted seismic catalogue was used to derive a minimum 1D velocity model. Then, we employed this model as an initial model to obtain the 3D velocity structure by jointly inverting for earthquake locations and lateral velocity variations. We will present results of the derived P-wave velocity and Vp/Vs models to highlight new information of the geothermal field and possible variations due to changes in fluid composition, rock porosity and temperature.

1. INTRODUCTION

The Los Humeros Volcanic Complex (LHVC) is presently one of the oldest producing geothermal fields in Mexico, and is a major geothermal target in the Trans-Mexican Volcanic Belt, with an installed capacity of ~95MW (Romo-Jones *et al.* 2018; Norini *et al.* 2019). Located in the state of Puebla, it is constituted by an older (ca 460 ka) 18-20 km wide circular caldera structure (Los Humeros caldera) and a younger (70 ka) 5-8 km wide inner caldera structure (Los Potreros Caldera) (Calcagno *et al.* 2018). From a geothermal point of view, the LHVC can be divided in four main groups: a pre-volcanic basement (limestone, shale, granite, and schist), an old volcanic succession or pre-caldera (mainly andesite), a caldera phase (ignimbrites and rhyolites), and a post-caldera phase (tuff, pumice, rhyodatice and andesite lava) (Calcagno *et al.* 2018).

Most of the injecting and producing wells are located within the inner Los Potreros caldera, where temperatures as high as 400°C have been measured at around 2.5 km. However geothermal fluids at these temperatures are currently not under exploitation. Despite the large number of wells drilled (~50) since the 90s, insights of the geothermal system below the current well penetration depths (~2.5 km) is still largely unknown. These facts raise the question of where these deep super-hot fluids lie, what is their behavior, and how to exploit them. In a broader sense, the study of the LHVC will also play a major role in understanding the characteristics of the geothermal resources in the region for further development.

2. MONITORING AND ANALYSIS OF LOCAL SEISMICITY

2.1 Seismic Network

Several geophysical, geochemical, and geological surveys have been conducted within the framework of the GEMex project to better characterize local and regional structures, to understand the behavior of the underlying geothermal system, and to identify possible new prospect targets. In this context, for a period of roughly one year (September 2017 - September 2018) a temporary seismic network consisting of 25 three-component broadband (Trillium Compact 120s) and 20 three-component short-period (Mark L-4C-3D) sensors was deployed and maintained to record continuous seismic data at 200 Hz and 100 Hz sampling rates, respectively.

The seismic network consists of two complementary sub-networks designed to comply for various processing techniques and answer different project objectives (Figure 1). A dense 27 station sub-network (~2 km inter-station distance) is located at the inner Los Potreros Caldera, where previous studies have highlighted the occurrence of local seismicity (Lermo *et al.* 2007; Urban and Lermo 2013), and where most of the injection and production activities take place. This sub-network is mainly intended for local seismicity retrieval, beamforming, SPAC (spatial autocorrelation), time-reverse imaging, and local earthquake tomography. A second much sparser network (~5-10 km inter-station distance) is located around the Los Humeros caldera and is intended for imaging larger scale structures with techniques like ambient noise tomography. From an earthquake location viewpoint, the network configuration was obtained using experimental network design tools (Toledo *et al* 2018).

2.2 Event Detection

We targeted the event detection mainly to the region within the Los Potreros caldera, where previous evidence for local seismicity exists, and where injection and production activities take place. To do so we first calibrated a recursive STA/LTA detection routine on local seismic events. These events were provided by the local Electric Company (CFE) using their own permanent seismic network. We used a combination of a bandpass filter between 10-30 Hz, STA and LTA windows of 0.2 s and 2 s, respectively, and on and off triggering thresholds of the computed STA/LTA function at 3.5 and 1.0, respectively. The STA/LTA ratio was calculated on a single amplitude trace corresponding to the square root of the sum of the squared single component traces. Finally, a detection was marked as one when the triggered window of at least 5 different stations from the dense sub-network coincide. Each detection was then manually reviewed and P and S phases of local events were picked with their corresponding uncertainty range. The described pre-processing, detection, and picking was performed using python Obspy (Beyreuther *et al.* 2018) and Obspyck (Megies *et al.* 2018) tools.

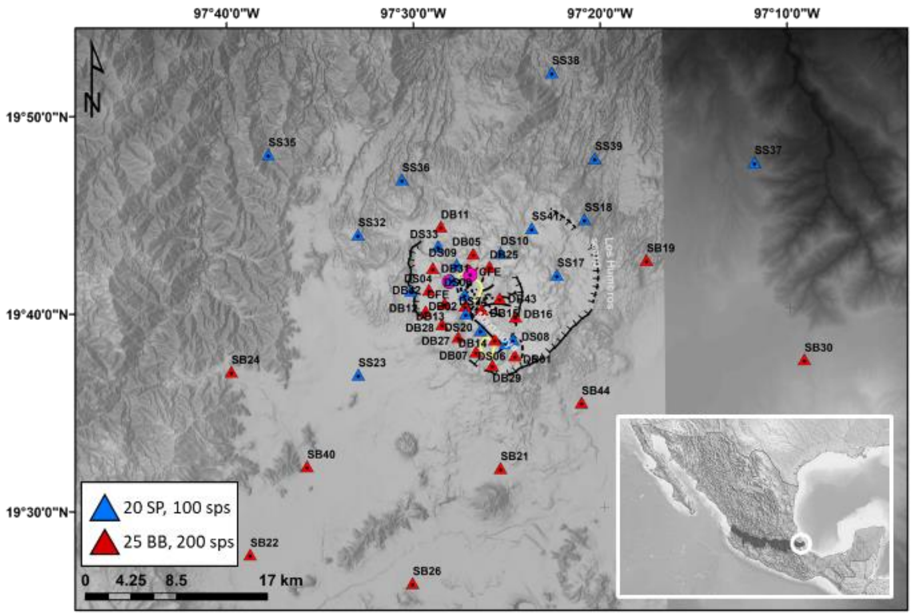


Figure 1: Seismic network deployed at the Los Humeros geothermal field. The red triangles mark the position of the three-component broadband stations, and the blue triangles, the location of the three component short period stations. The main structures and faults inferred at surface are marked in black (modified from Norini *et al.* 2015; Carrasco-Núñez *et al.* 2017).

3. MINIMUM 1D VELOCITY MODEL

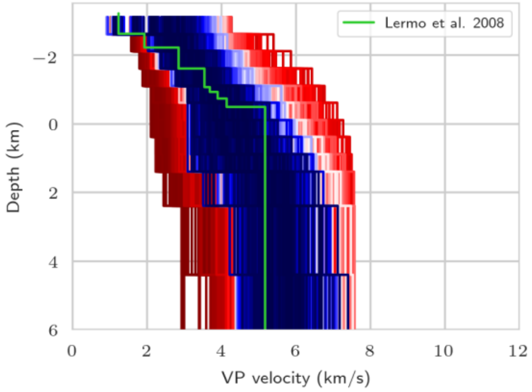
A total of 488 local events were extracted from the 1586 detections. These earthquakes were then initially located using an oct-tree search over a homogeneous 3D volume of 3.5 km/s Vp velocity and 1.73 Vp/Vs ratio (Lomax *et al.* 2000). Later, we pre-selected the events with azimuthal gap of less than 180°, and with at least 3 P and 3 S wave arrivals (360 events in total) for the calculation of a minimum 1D velocity model. The filtered 360 event catalog was then used as input for a joint inversion using the code Velest (Kissling *et al.* 1994) to obtain a minimum 1D Vp and Vs models along with event relocations.

We performed the inversion of approximately 5000 initial models with varying gradients and Vp velocities at surface, and starting Vp/Vs ratios (hence, varying Vs models), all located at the center of the geothermal field (19.67° latitude and -97.45° longitude). Later, we compared the results and selected the models with lowest associated RMS as an initial reference for the 3D seismic tomography.

Figure 2a depicts all the resulting Vp models sorted by their RMS value, blue indicating lower, and red indicating higher misfits. A previous 1D P-wave velocity model for LHVC (Lermo *et al.* 2007) is marked in green. Figure 2b shows the newly computed minimum 1D Vp and Vs models, Figure 2c shows the resulting Vp/Vs ratio, and Figure 3d shows the event distribution after the joint inversion. Most of the seismicity is located between 1 and 3 km below the surface, with a maximum of the events localized at approximately 2.5 km below surface (ca 0 km depth). This region correlates with the currently exploited reservoir interval, with a maximum well depth at around 2.4 km below surface. The resulting event distribution allows to extend with confidence the previous 1D Vp velocity reference (maximum ~2.3 km below surface) to ~4-5 km depth below surface.

The resulting 1D velocity models show a series of sharp boundaries at around -2 km, -1 km, and 1.5 km depth (horizontal orange lines in Figure 2). These boundaries could potentially be marking the limits between the LHVC, an old volcanic succession, the sedimentary basin, and the Teziutlan Massif as inferred by well data in Norini *et al.* 2019.

a)



b) c) d)

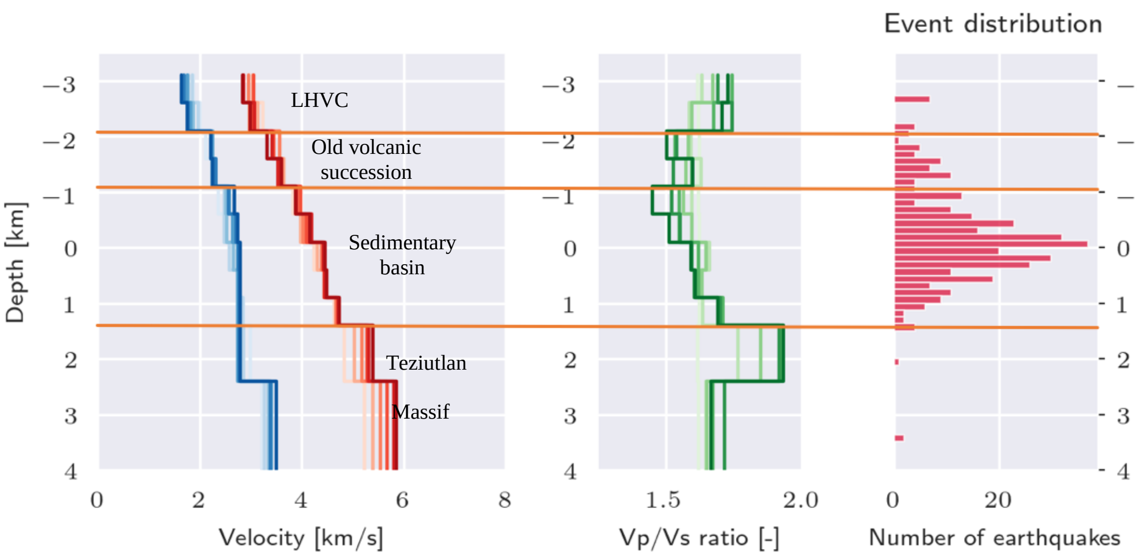


Figure 2: Minimum 1D velocity model inversion. a) Final Vp models after inverting for different initial velocity models. Models are sorted by color. Lower RMS values are marked in blue, and models with higher RMS values are marked in red. b) Minimum 1D Vp (red) and Vs (blue) velocity models and their iterations. Stronger colors mark the results of the final iteration. c) Resulting Vp/Vs ratio and its iterations. Stronger colors mark the results of the final iteration. d) Histogram for the event distribution. Orange horizontal lines mark possible unit boundaries that could potentially correlate with the interpreted well data shown in Norini *et al.* 2019.

4. 3D JOINT INVERSION

To study the 3D velocity structure and relocate more precisely the seismic events, we use the simultaneous 3D inversion code SIMUL2000 (Thurber *et al.* 1983; Eberhart-Phillips 1990; Evans *et al.* 1994; Eberhart-Phillips and Michael 1998). The program performs a damped iterative least-squares inversion that aims to obtain the velocity model and source locations that would best explain or fit the data (P- and S-phase travel time picks). SIMUL2000 allows for the inversion of Vp and Vp/Vs ratio instead of Vs. The Vp/Vs ratio and its corresponding Poisson ratio are sensitive to fractures, rock porosity, lithology, temperature, and variations due to fluid composition changes which are vital for the understanding of a geothermal system.

We use the previous 1D models and hypocenter locations as initial values to perform a graded 3D inversion. In other words, we iterate through finer and finer grids, using each coarse model output as input for a new inversion with a finer grid. In this study, we inverted for Vp and Vp/Vs models using first an inter-grid spacing of 5 km, then refined to 2 km and finally to 1 km inter-grid spacing. Damping values at each stage were empirically determined from tradeoff curves between model and data variance (Eberhart-Phillips 1990). Similar inversions were performed after rotating the grid every 5°, and then all results were combined by averaging all outputs into a single output grid.

Figure 3 shows the spatial distribution of the resulting earthquake catalog and its associated ray path configuration, after the final inversion step. The recorded seismicity is mostly located below the dense array within the Los Potreros caldera, and grouped into three distinctive clusters. The northernmost cluster has already been evidenced in Lermo *et al.* 2007, and it is situated below the main production area, where two out of the three injection wells are located. The southwestern cluster is located west to the Los Humeros fault, close to a third injection well. Finally, a deeper cluster is located towards the east, between the Las Papas and the Arroyo Grande faults. The remainder seismicity lies mostly along the Maxtaloya fault, with some events scattered within the inner Los Potreros caldera, and few events towards the northwest.

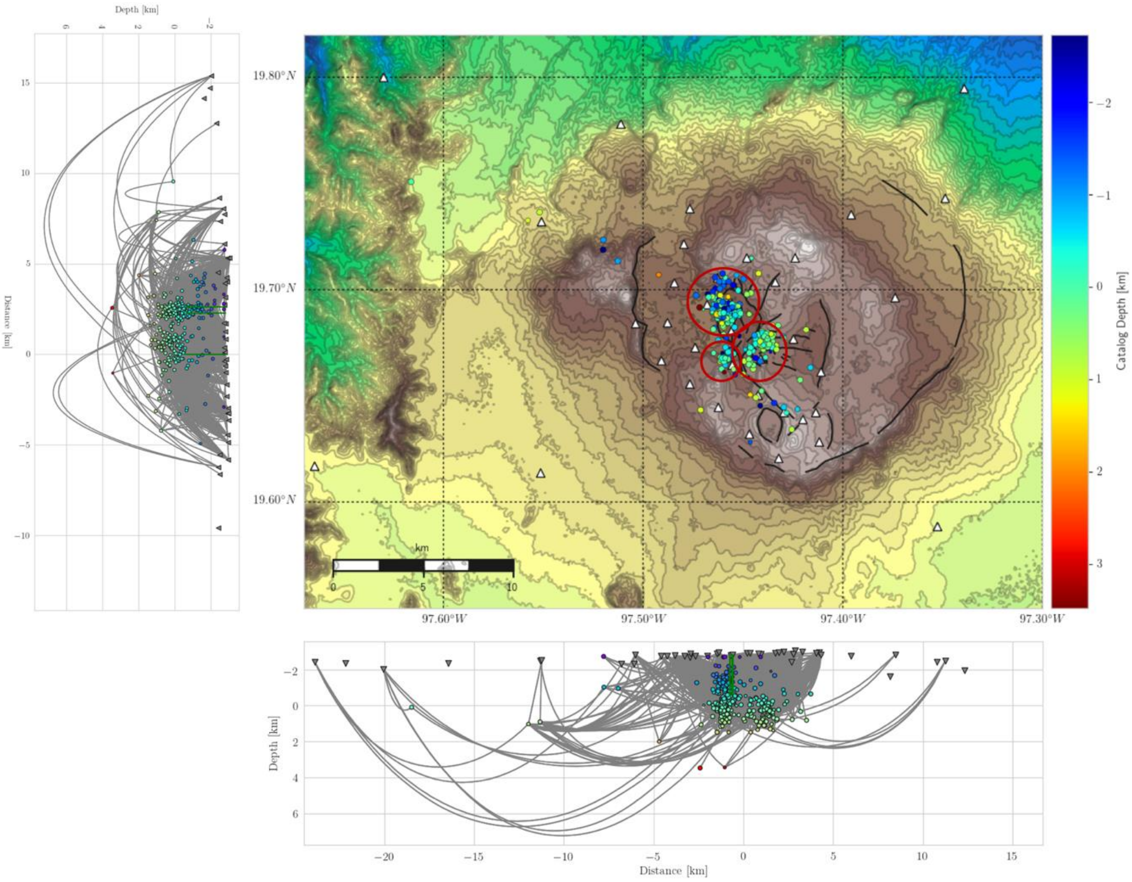


Figure 3: Spatial distribution and ray paths of the resulting earthquake catalog after the 3D inversion. The red circles indicate the locations of three distinctive earthquake clusters. The bottom and left panels show the ray paths and event location projections. The green lines within the depth slices represent the projections of the three active injection wells. The color bar indicates the depth of the seismic events.

Figure 4 depicts tomographic images at different depths: -2.6 km (~300 m from the surface), -1.6 km and -0.50 km, and Figure 5 shows an east-west cross section with its corresponding Vp variation and Vp/Vs ratio models. As seen in figures 4a, 4c, and 4e (marked with number 1), a higher Vp anomaly is located at the center of the Los Potreros caldera, especially within the region with higher fault density. This same area experiences later a velocity decrease at around -0.2 km depth (A-A' cross section in Figure 5a), which may correspond to the boundaries of the sedimentary basin.

A lower C-shaped Vp velocity anomaly is located at the east of Los Potreros caldera (Number 2 in Figure 4a and 4c). This anomaly generally disappears at greater depths, but remains at the southern side, on top of the Xalapasco crater and towards the west (Figure 4e). The shallow C-shaped anomaly matches the region where post-caldera monogetic volcanic centers are located (Norini *et al.* 2019). These anomalies are also evident in the shallow east portions of cross section A-A' (Number 5 in Figure 5a).

Vp velocity contrasts also evidence a few structures also seen in MT resistivity cross-sections in Arzate *et al.* 2018, and some mapped at surface (Norini *et al.* 2019). Los Humeros fault for example, appears clearly with the aligned seismicity, close to the injection well (Figure 5).

As in the case for the Vp model, there is a high Vp/Vs ratio anomaly towards the northeast at shallow depths (Number 3 in Figure 4b and Number 6 in Figure 5b), where the volcanic centers lie. Another high Vp/Vs anomaly appears at depth towards the northwest (Number 4 in Figures 4d and 4f, and Number 7 in Figure 5b). High Vp/Vs areas could be indicators of hot fluids, however additional well data and results from alternative geophysical methods will be required to validate them as such.

5. CONCLUSION AND PERSPECTIVES

Overall the year-long passive seismic experiment has been successful in providing valuable insights on the reservoir structure and hinted on potential areas bearing hot fluids. However, it is vital to further integrate these results with different geophysical techniques, along with core measurements for a comprehensive and robust interpretation of the geothermal field.

6. ACKNOWLEDGEMENTS

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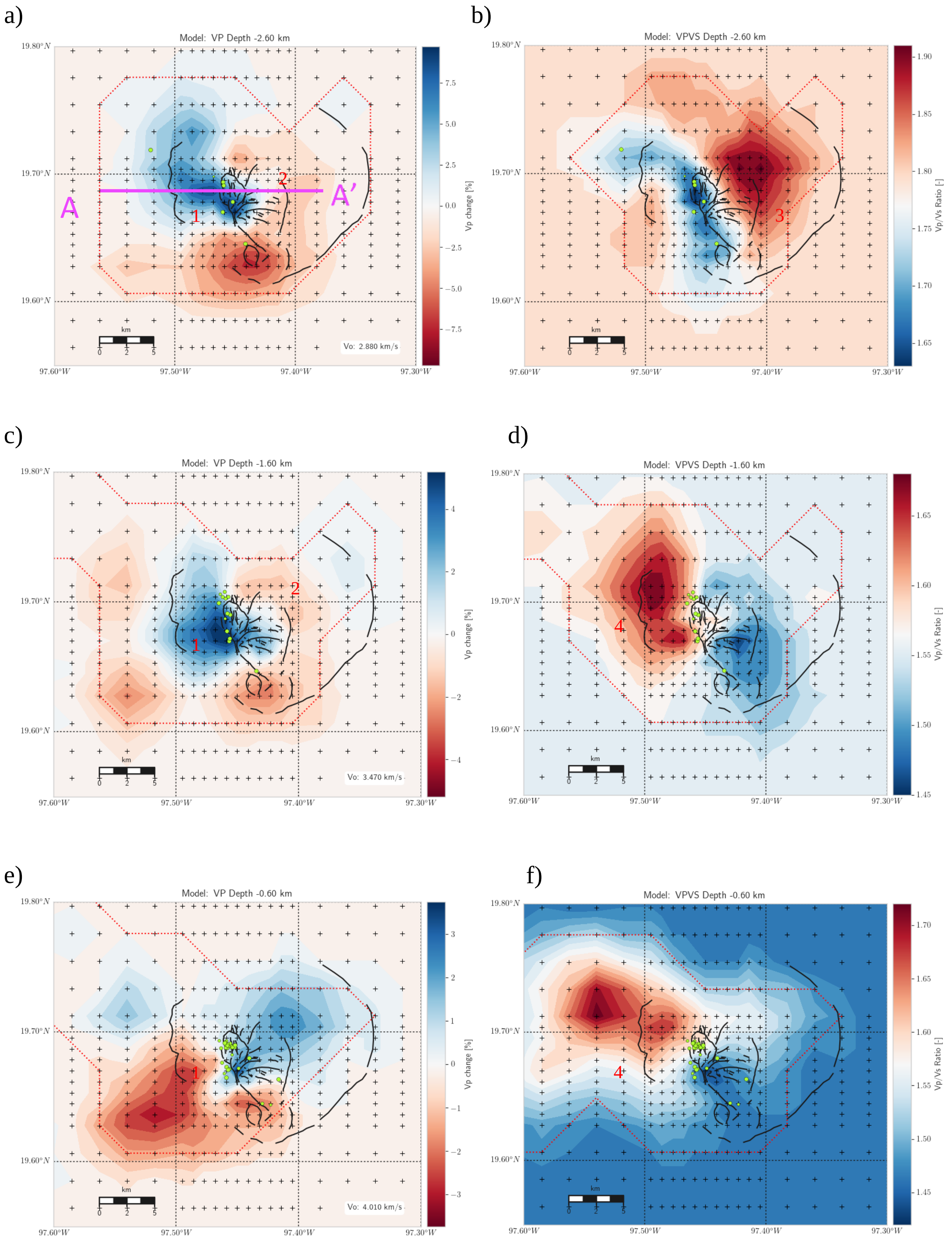

Figure 4: Vp variation (left column) and Vp/Vs (right column) models at three different depth slices. The velocity reference Vo for the velocity variation is taken from the retrieved 1D velocity. Main surface faults and structures are marked in black (modified from Norini et al. 2015; Carrasco-Núñez et al. 2017). The dotted red lines mark the limit where the diagonal element of the model resolution matrix is higher than zero. Node points are marked as black crosses. Green circles correspond to the seismicity at 150 m below and above the shown depth. An east-west cross section is marked in magenta in panel 4a. Red numbers indicate some areas of interests which are described within the text.

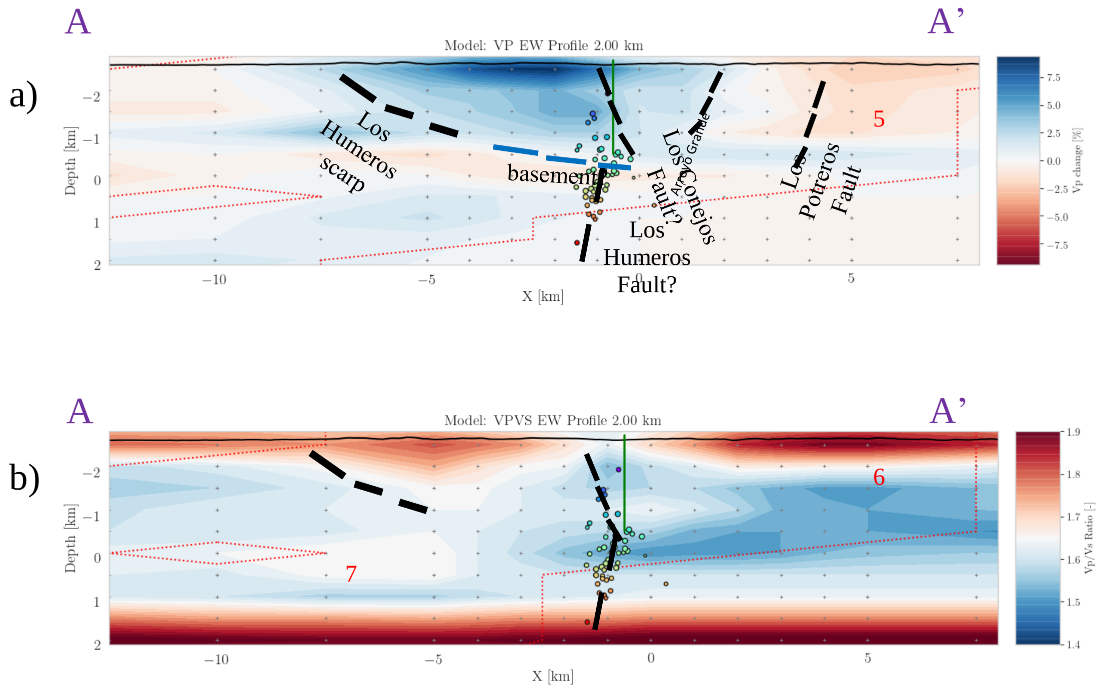

Figure 5: A-A' cross section for a) Vp variation and b) Vp/Vs structures. The location of the cross section is shown in Figure 4a. The dotted red lines mark the limits where the diagonal element of the model resolution matrix is higher than zero. Node points are marked as black crosses. Small circles correspond to the seismicity up to 250 m away from the slice. Green lines mark the position of a neighboring injection well. The segmented black and blue lines mark some inferred structures, and red numbers indicate some areas of interest. More explanation is described within the text.

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