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## RESEARCH ARTICLE

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### Key Points:

- A new crustal earthquake catalog reveals the details of active faults and stress field orientations in the Southern Puna plateau
- Observed stress regimes can be associated with the varying influences of plate convergence, crustal flow, and flat slab subduction
- An earthquake swarm below Cerro Galan occurred over a 10-day period and within a depth range of 0–4 km

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Seismicity and Present-Day Crustal Deformation in the Southern Puna Plateau

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**Abstract** The Southern Puna plateau in the central Andes has a complicated tectonic history that includes episodes of distributed shortening and extension, lithospheric delamination, uplift and Quaternary backarc volcanism. In this study, the upper crustal structure and present-day deformation in this area is investigated using a new regional earthquake catalog derived with a deep-learning-based phase picker. Results show abundant strike-slip seismicity at shallow depths in the eastern Southern Puna plateau that reveals active fault systems in the area and indicates N-S extension/E-W compression that changes orientation and relative magnitude from north to south. A broad zone of seismic quiescence in the western plateau may indicate a zone of upper crustal decoupling from large-scale deformation. The region separating the western and eastern plateau exhibits a complex stress field that can be related to the boundary of east/west oriented middle-to-lower crustal flow in the main volcanic arc. Southeast of the plateau in the Sierras Pampeanas, crustal seismicity deepens and is dominated by conjugate reverse faulting structures associated with the direction of plate convergence. V<sub>p</sub> and V<sub>s</sub> seismic velocity models of the upper crust obtained through local earthquake tomography with the improved seismic catalog show low-velocity anomalies near intermontane basins, except in the Antofagasta basin where a high-velocity anomaly possibly represents shallow intrusive component of Quaternary basaltic volcanism. Below the Cerro Galan caldera, an upper crustal 10-day long earthquake swarm is observed which may indicate local stress perturbations from fluids at the top of the crustal magmatic system that feeds this volcano.

**Plain Language Summary** The Southern Puna plateau in the central Andes has a complex tectonic history with alternating episodes of extension and compression, and young volcanism. In this study, a new earthquake catalog is obtained for this region by using machine-learning for seismic phase picking. This catalog contains 10 times more earthquakes compared to previous catalogs, constrains the faults accommodating present-day deformation, and estimates variations in crustal stress in this region. Results show abundant strike-slip faulting earthquakes in the eastern plateau, and very few earthquakes in the western plateau. The transition zone between these two areas exhibits a complicated stress field possibly associated with the boundary of middle-to-lower crustal flow that inhibits large-scale deformation in the upper crust of the western plateau. Further east, in the Sierras Pampeanas, deep crustal earthquakes reveal the reverse faulting structures along which deformation associated with plate convergence is accommodated. Upper crustal 3D seismic velocity models reveal high velocities associated with solidified mafic magma from young basaltic volcanism, and low velocities in local basins. Beneath the Cerro Galan caldera, a 10-day sequence of small earthquakes (seismic swarm) is detected in the upper crust possibly due to migrating fluids from the underlying magma system.

## 1. Introduction

The most prominent topographic feature of the Andes Mountain Range is the broad, high-elevation Altiplano-Puna plateau of the Central Andes (Figure 1) which formed due to multiple processes related to crustal shortening and thickening caused by subduction of the Nazca Plate beneath the South American Plate (Allmendinger et al., 1997; Isacks, 1988; McQuarrie et al., 2005). This plateau has a length of approximately 1,800 km, extending from southeast Peru to northwest Argentina, and is bordered by Peruvian and Chilean-Pampean flat slab subduction to the north and south, respectively (e.g., Cahill & Isacks, 1992).

The Puna plateau to the south is distinguished from the Altiplano plateau to the north by its higher elevation, rugged topography, small basins separated by ranges exhumed along high-angle reverse faults and distributed deformation (e.g., Allmendinger et al., 1997). The Puna plateau is divided into northern and southern parts by the NW-SE trending Olacapato-Toro-Lineament (O-T-L) at around 25°S (e.g., Allmendinger et al., 1997), and the Southern Puna plateau is further segmented by additional NW-SE trending lineaments that coincide with major

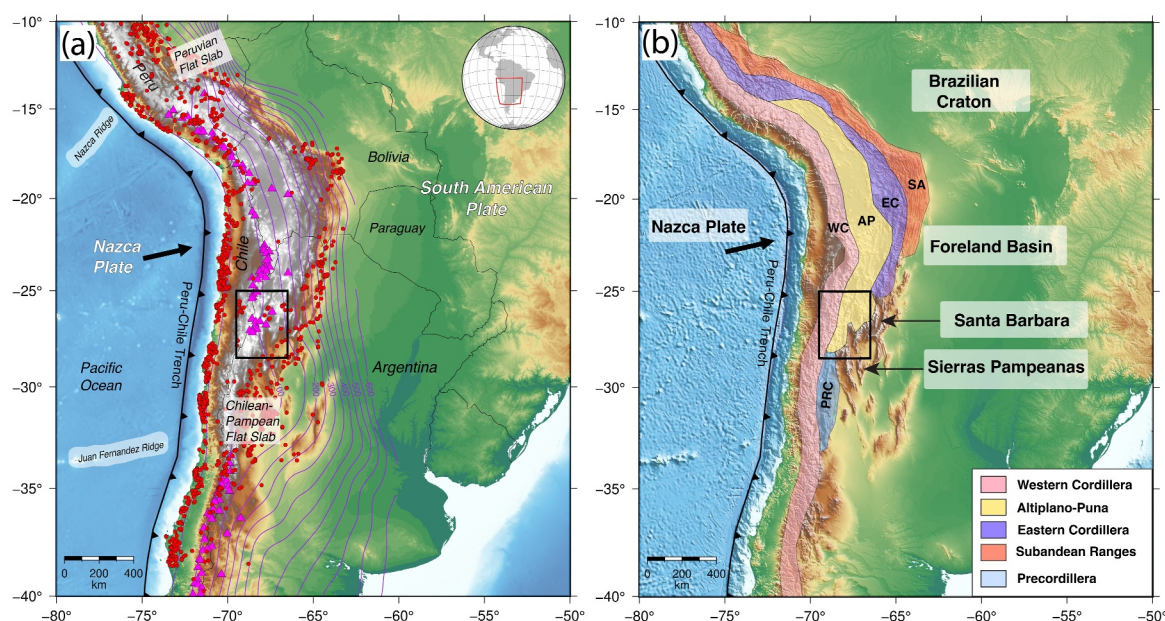


**Figure 1.** (a) Map of central South America showing Andean topography, subduction of the Nazca Plate along the Peru-Chile Trench, subducting ridges, and flat slab regions. The purple contours indicate the slab depth (Slab 2.0: Hayes et al., 2018), and the pink triangles are the Holocene volcanoes along the main volcanic arc (Global Volcanism Program, 2024). The black arrow indicates the subduction direction of the Nazca plate. Red circles show teleseismically constrained crustal seismicity from the ISC-EHB Bulletin (Engdahl et al., 1998, 2020; International Seismological Center, 2024; Weston et al., 2018). The solid black box indicates the study area. The inset shows the global position of central South America. (b) Major morphotectonic units along the Andean Mountain Belt.

back-arc volcanic centers (e.g., Báez et al., 2023; Chernicoff et al., 2002). Moreover, uplifted NE-SW oriented ranges (e.g., Sierra Calalaste, Sierra Blanca, and Sierra Filo Colorado) have segmented the plateau into several internally drained basins (e.g., the Antofagasta and Pasto Ventura Basins). To the east, the plateau is bordered by west-verging, high-angle reverse faults of the Santa Barbara system north of 27°S and thick-skinned basement uplifts of the Sierras Pampeanas (Allmendinger et al., 1997) to the south (Figure 2).

Crustal deformation in the Southern Puna plateau has been dominated by orogen-perpendicular shortening and orogen-parallel extension since the late Miocene (Allmendinger et al., 1989; Montero Lopez et al., 2010; Schoenbohm & Strecker, 2009; Zhou et al., 2013). This orogen-parallel extensional deformation has been accommodated by young and disorganized normal and strike-slip faulting (e.g., Schoenbohm & Strecker, 2009). The region has also experienced local episodes of orogen-oblique extension on N-S or NE-SW oriented strike-slip and normal faults during this time (Schoenbohm & Carrapa, 2015). These observations have been associated with lithospheric foundering which is also thought to be a driver of back-arc volcanism in this region (Kay & Coira, 2009; Kay et al., 1994; Kay & Kay, 1993), as well as lower crustal flow (Kay et al., 2014).

Several geophysical studies have investigated the Southern Puna plateau, though much of this work has focused on the deeper structures of the lower crust and upper mantle as they relate to episodes of delamination (Bianchi et al., 2013; Calixto et al., 2013; Chen et al., 2020; Heit et al., 2014; Liang et al., 2014). In general, the crust of the Altiplano-Puna plateau is weak and felsic in composition with low seismic velocities (Beck & Zandt, 2002). Previous research that has focused on the crustal structure of the Southern Puna plateau has imaged multiple zones of low velocity, high Vp/Vs, or low electrical resistivity in the middle-to-lower crust that have been inferred to represent magma reservoirs that fed the eruption of felsic-to-intermediate ignimbrites (e.g., Bianchi et al., 2013; Delph et al., 2017; Heit et al., 2014; Unsworth et al., 2023). This crustal magma chamber interpretation is also in agreement with geochemical studies of the volcanic products in this area (Kay et al., 2010, 2011; Risse et al., 2013). Though geodetic observations on the Puna plateau are sparse, the closest studies to this area indicate that most of the present-day back-arc shortening is accommodated by the Eastern Cordillera with very little deformation observed in the Puna plateau (e.g., McFarland et al., 2017). Mulcahy et al. (2014) investigated crustal seismicity in this region utilizing the same data set used in the current study. Notable results from this previous work include generally sparse and shallow seismicity (<5 km) on the plateau that deepens to the southeast in the

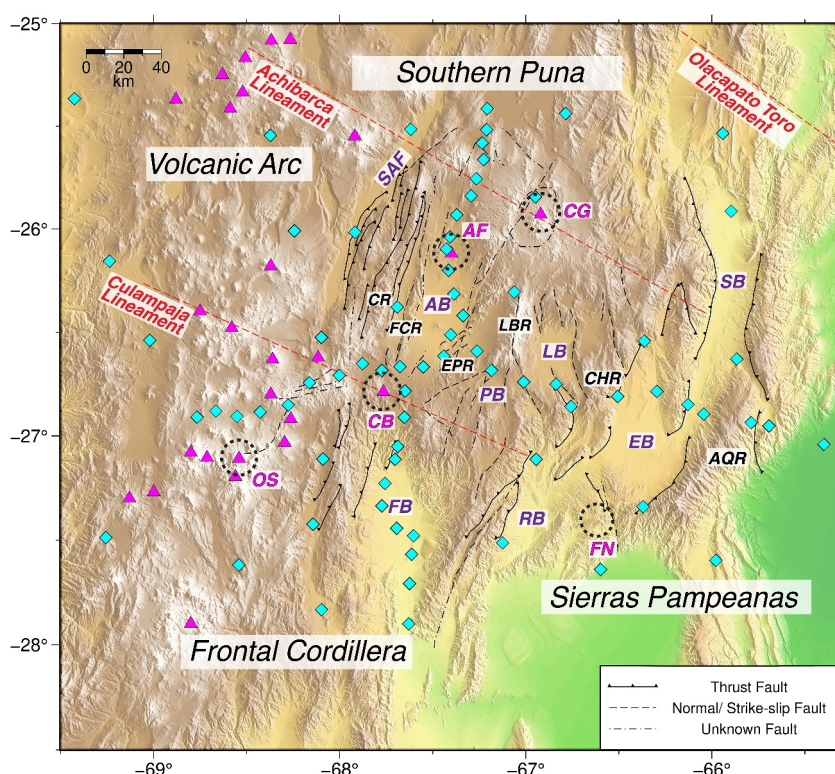


**Figure 2.** Map of the Southern Puna plateau with the main volcanic arc and frontal cordillera to the west and Sierras Pampeanas to the east. Pink triangles indicate the Holocene and Pleistocene volcanoes obtained from the Global Volcanism Program (2024) with major back-arc volcanoes (CG: Cerro Galan, AF: Antofagasta, CB: Cerro Blanco, FN: Farallon Negro, OS: Ojos del Salado) marked with circles. The red dashed lines show the major NW-SE lineaments in this area. Major mountain ranges (CR: Calalaste Range, FCR: Filo Colorado Range, EPR: El Peñon Range, LBR: Laguna Blanca Range, CHR: Chango Real Range, AQR: Aconquija Range), basins (SAF: Salar de Antofalla, PB: Pasto Ventura Basin, FB: Fiambala Basin, AB: Antofagasta Basin, SB: Santa Maria Basin, EB: El Cajon Basin, RB: Rio Bolson Basin), and mapped faults digitized from Cristallini et al. (2004), Risse et al. (2008), Zhou et al. (2013), Mulcahy et al. (2014), and McMillan et al. (2022) are also shown in the figure. The blue diamonds indicate the station locations from the Southern Puna Seismic Project (Heit et al., 2007; Sandvol & Brown, 2007).

Sierras Pampeanas, clusters of seismicity near volcanic regions such as Cerro Galan and Cerro Torta, and strike-slip and oblique normal and reverse faulting focal mechanisms that indicate east-west compression and north-south extension.

Improving the crustal earthquake catalog of the Southern Puna plateau can provide insights into several outstanding questions about the plateau that have not been addressed in previous studies. For example, though the sparse and shallow seismicity in the plateau has been primarily attributed to a hot and weak crust that causes a shallow brittle to ductile transition, another possible cause of this sparsely observed seismicity could be poor seismic phase detection due to attenuation of seismic phases, particularly S waves, due to the generally low Q values associated with volcanic settings. Furthermore, sparse seismicity is an attribute of the interior of much of the Andes based upon global earthquake catalogs and may be associated with a lack of upper crustal deformation due to deeper crustal processes like detachment faults or lower crustal flow (e.g., Babeyko et al., 2006). However, few studies have interrogated these zones of seismic quiescence using low magnitude of completeness earthquake catalogs. Details of the stress field of the Southern Puna plateau constrained from focal mechanisms can also be investigated with an improved earthquake catalog. These details include the relationships between present-day local stress perturbations in the Southern Puna plateau and foundering processes in the underlying lower crust and mantle, as well as the transition in the stress field from the plateau to the Sierras Pampeanas to the east. Finally, the sparse crustal seismicity presented in previous studies has the effect of limiting the resolution of tomography models of the upper crust in this region. An updated tomography model developed by using an improved crustal earthquake catalog can be valuable for constraining the geometries of basins and the shallow

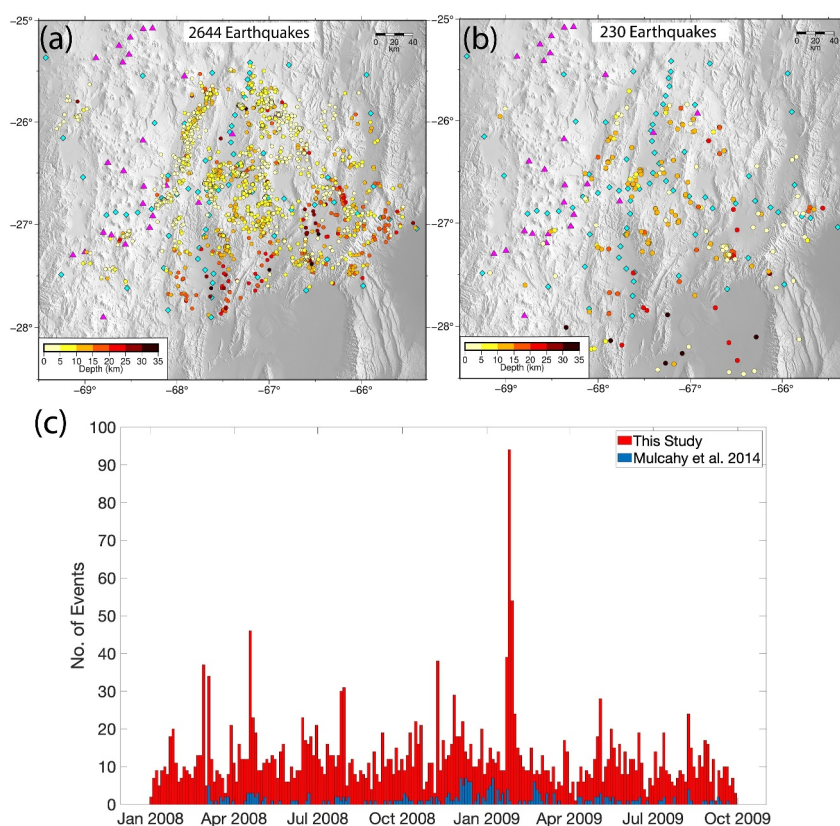


**Figure 3.** (a) Distribution of crustal seismicity located in this study color coded by depth. (b) Distribution of well-constrained crustal events obtained from a previous study (Mulcahy et al., 2014) with the same data set. Note that earthquakes located outside of the seismic array footprint would not meet the  $180^\circ$  station azimuthal gap constraint applied to the earthquake catalog of the current study. (c) Comparison of the number of detected crustal earthquakes in the current study (red) with the previous study (Blue, Mulcahy et al., 2014) through an event frequency histogram. Other symbols in (a) and (b) are the same as Figure 2.

portions of the massive middle to lower crustal magma bodies that have been previously imaged in this region (e.g., Bianchi et al., 2013; Chen et al., 2020; Delph et al., 2017; Heit et al., 2014; Liang et al., 2014).

In this study, seismic phases from crustal earthquakes in the Southern Puna plateau and the adjacent Sierras Pampeanas are detected using PhaseNet, a deep-neural-network based phase-picker (Zhu & Beroza, 2019), which automatically identifies P and S arrivals in unfiltered, continuous seismic data. This method has outperformed traditional phase-pickers in previous studies by increasing the identification of low-amplitude phases which improves the detection of lower magnitude events, leads to higher resolution hypocentral locations for earthquakes of all magnitudes, and improves ray coverage for body wave tomography inversions (e.g., Ammirati et al., 2022; Liu et al., 2020). Using the travel times and polarities of seismic phases from detected earthquakes, absolute and relative earthquake locations, focal mechanisms, principal stress orientations, and upper crust  $V_p$  and  $V_s$  models are constrained within the plateau and adjacent Sierras Pampeanas region.

## 2. Data

A seismic array of 74 stations was deployed in the Southern Puna plateau as part of the Southern Puna Seismic Project (Heit et al., 2007; Sandvol & Brown, 2007; Figure 2), which recorded continuously from December 2007 to October 2009. Out of those 74 stations, 13 broadband stations and 35 intermediate-period stations were installed with 10–20 km spacing on two perpendicular arrays approximately parallel (north-south) and perpendicular (east-west) to the trench. The other 26 broadband stations formed a 2D sparse array with 35–50 km spacing. Based on the consistent availability of data throughout the network, in this study, we have used 21 months of broadband and intermediate-period seismic data (January 2008 to September 2009) recorded on

these stations. The continuous seismic waveforms are obtained from the archives at the Earthscope consortium and the GEOFON Data Center. Note that at the time of writing this manuscript, the metadata for stations BB03 and BB04 require location corrections. The correct station coordinates can be obtained from Mulcahy et al. (2014).

### 3. Materials and Methods

In this study, seismic analysis tools organized under the LOC-FLOW framework (Zhang et al., 2022) are used to detect, locate, and estimate magnitudes of earthquakes that occur within the footprint of the seismic network (Figure S1 in Supporting Information S1). A deep neural-network-based phase picker (PhaseNet) trained using data and manual picks from Northern California (Zhu & Beroza, 2019) is used to identify P and S seismic phases in 21 months of continuous three-component waveform data from the Southern Puna plateau. For each point in the time series, a cut-off probability of 0.5 is used to identify true seismic phase arrivals. A grid search method is used to associate seismic arrivals with seismic events (REAL; Zhang et al., 2019) using the depth-averaged 1D velocity model from Bianchi et al. (2013). To reduce the false positives due to the usage of a simple 1D model, strict thresholds of at least five P phases, five S phases, fifteen total phases and five stations recording both P and S arrivals have been used. In addition, all events must be recorded with an azimuthal gap less than 180°. Hypocenters from earthquakes that meet these constraints are further updated with simulated annealing optimization (Kirkpatrick et al., 1983; Zhang et al., 2019), which is a non-linear optimization algorithm useful for avoiding local minima and converging to a global minimum solution.

To obtain a regional 1D velocity model and refine hypocenter locations, the VELEST algorithm is applied (Kissling et al., 1994), which inverts for a minimum-misfit 1D velocity model jointly with station corrections and hypocenter locations by minimizing the travel time residuals between theoretical and observed arrivals. The 1D velocity model from Bianchi et al. (2013) is used as a starting velocity model and multiple iterations are performed until residuals no longer decrease. Since low velocity layers cause instability in the solution, these features are not allowed in this inversion. However, the 3D travel time tomography at a later stage of the workflow would permit low velocity zones to be observed if present in the study area. As a final step for refining the earthquake hypocentral locations, a double-difference earthquake relocation algorithm is applied (HypoDD; Waldhauser & Ellsworth, 2000), which adjusts the relative position between two nearby earthquakes by minimizing the residual of their differential travel times. Since the hypocentral distance between two nearby events is significantly smaller than the distance to seismic stations and the scale of lateral heterogeneities, the travel time differences mostly originate from the hypocenter offsets (Waldhauser & Ellsworth, 2000). Hence, this approach nullifies lateral velocity variations along the ray paths and gives well-constrained earthquake locations within the best-fitting 1D velocity model. Only a subset of the earthquakes with nearby neighboring events located within 10 km are relocated in this step of the analysis. The hypocentral depths in the final earthquake catalog from both the VELEST and HypoDD analysis are reported with respect to sea level (see earthquake catalog in Supporting Information S1), though we will also discuss these depths with respect to the average surface elevation in later sections.

Local magnitudes for the earthquake catalog are estimated from body-wave amplitudes. After removing the original instrument response, the resulting time series is convolved with the instrument response of a Wood-Anderson seismograph. Following this step, the peak amplitude of P and S waves is used with an empirical relationship (Hutton & Boore, 1987) to calculate local earthquake magnitudes ( $M_L$ ). For a subset of well-recorded earthquakes, a focal mechanism analysis is performed. As most of the earthquakes have magnitudes less than 3.0, the events are not suitable for waveform modeling. However, the relatively large events ( $M_L > 2.5$ ) or the events close to the center of the array ( $2.0 > M_L > 2.5$ ) have clear P arrivals and are well-recorded across the seismic network. Hence, P-wave first motion polarities are used to constrain event focal mechanisms with the FOCMEC algorithm (Snook, 2003). The first-motion polarities are obtained by hand-picking for each event. The azimuth and take-off angle of the rays traveling from the source to the station are computed with the TauP program (Crotwell et al., 1999) based on the 1D velocity model. A grid search of strike, dip, and rake angle with 5° increments is performed which provides several possible mechanisms that fit the polarity observations. The group of potential focal mechanisms are used to calculate a mean focal mechanism, and associated statistical uncertainties, for each event. The well-constrained focal mechanism solutions (strike, dip, and rake errors less than 30°) are further used to obtain the present-day crustal stress orientation on the plateau. The strike, dip, and rake of these earthquakes are used for jointly inverting for the relative stress tensor components and fault planes through

an iterative linear inversion (Vavryčuk, 2014). The relative magnitudes of principal stress values are represented through the shape ratio ( $R$ ) where,  $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$ . The stability of the principal stress axes and shape ratios is estimated by performing 200 inversions in which random noise with a mean of  $15^\circ$  is added to the focal mechanisms (strikes, dips, and rakes). This mean error value of  $15^\circ$  is chosen based on the mean standard deviation derived from the previously described focal mechanism solutions. As a final step in the analysis, travel times from located earthquakes are used to model 3D P-wave and S-wave seismic velocities in this region. Earthquake locations and the 1D velocity model obtained from VELEST are used as the starting parameters for the LOTOS tomography algorithm (Koulakov, 2009), which models 3D seismic velocity anomalies by minimizing travel time residuals. The model space is a  $140 \times 140 \times 20 \text{ km}^3$  gridded volume with grid spacing of  $4 \text{ km} \times 4 \text{ km} \times 1 \text{ km}$  for the east/west, north/south, and depth directions, respectively. Optimum damping and smoothing parameters for this inversion are obtained from the trade-off curves of model and data variance (Figure S15 in Supporting Information S1). The inversion is performed simultaneously for P and S velocity anomalies, earthquake hypocenters, and station corrections.

## 4. Results

In total, 3,087 crustal earthquakes are initially detected, and 2,644 earthquakes are well-constrained within the best-fitting 1D velocity models. The initial and final velocity models, residual distributions, and station corrections are shown in Supporting Information S1 (Figures S2 and S3). To check the robustness of the 1D velocity models, the inversions are repeated using starting models with higher and lower velocity values. The resulting 1D models exhibit only minor differences from the original results (Figure S4 in Supporting Information S1). Inversions are also performed using starting velocity models from Delph et al. (2017) and Chen et al. (2020) with little effect on the final results. This indicates that the model is robust and represents a global minimum solution. To check the stability of the hypocenters, the latitude, longitude, and depth of each event is randomly shifted by 10 km and the inversion is repeated. Results show stable longitudes and latitudes (standard deviation of 469 m and 615 m respectively), but a larger standard deviation in depth of 2.3 km (Figure S4 in Supporting Information S1). The catalog of earthquakes relocated by the double-difference inversion contains 2,130 events and the uncertainties associated with these hypocenters are analyzed using a bootstrap resampling method (Waldhauser & Ellsworth, 2000). Random noise is sampled from the final residual distribution and added to the differential travel times. The inversion is performed 200 times with the noise-added differential travel times and the deviation of the locations are measured from the final location. The resultant mean deviation of latitude, longitude and depth for each event is considered as the error bound for the event. Considering the  $2\sigma$  boundary of a Gaussian distribution, the latitude and longitude errors are within 250 m and 244 m respectively. However, the depths have a higher error bound of 1.2 km (Figure S6 in Supporting Information S1).

### 4.1. Regional Distribution of Seismicity

The event distribution map after double-difference relocation is shown in Figure 4. Many of the earthquakes align with faults adjacent to uplifted ranges and there is a general dearth of seismicity within the basins of the region. There is a large cluster of seismicity along the NE-SW trending fault system to the east of Salar de Antofalla. To the west of the salar, no events are detected beneath the volcanic arc, and additional events to the west are not detected until reaching the margin of the seismic array, significantly west of the arc. East of the salar, the Calalaste range and adjacent Antofagasta basin almost completely lack seismicity. Several clusters of earthquakes are located to the south of the Antofagasta basin, near the center of the seismic array (Figure 4). This seismicity includes a large cluster at the southern edge of the Filo Colorado range, several events concentrated along the NE-SW trending faults in the El Peñon region, and a NW-SE trending cluster of relatively deep ( $\sim 5\text{--}12 \text{ km}$ ) events in the southern Antofagasta basin. To the east of this central region, there is significant seismicity surrounding the Pasto Ventura basin, however, the Pasto Ventura basin itself mostly lacks seismicity. To the northeast of this central region, a series of NW-SE trending earthquakes are located along the Achibarca lineament and adjacent to the Cerro Galan caldera.

Volcanic regions such as Cerro Galan, Ojos del Salado and the Cordillera San Buenaventura volcanic field also host abundant seismicity. Beneath Cerro Galan caldera, 164 well-constrained events are located which occurred within a 10-day interval (22 January 2009–4 February 2009). In the western part of the Buenaventura volcanic field, earthquakes orient in the NE-SW direction following the faults in the Cerro Torta dome region. However, no

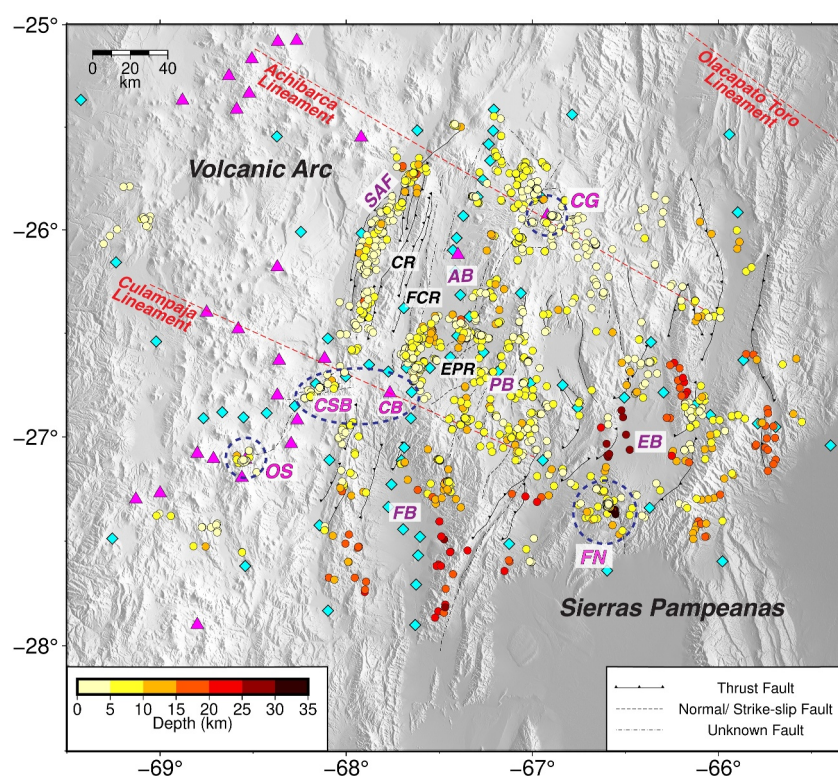


**Figure 4.** Map of seismicity distribution after double-difference relocation color coded by depth on grayscale topography. The dark blue dashed circles/ellipses indicate the earthquakes under volcanic centers. Relevant ranges (CR: Calalaste Range, FCR: Filo Colorado Range, EPR: El Peñon Range), basins (SAF: Salar de Antofalla, AB: Antofagasta Basin, PB: Pasto Ventura Basin, FB: Fiambala Basin, EB: El Cajon Basin), volcanic fields (CG: Cerro Galan, CSB: Cordillera San Buenaventura, CB: Cerro Blanco, FN: Farallon Negro, OS: Ojos del Salado), and lineaments are labeled in the map. Other symbols are the same as Figure 2.

seismicity is detected in the eastern flank of the Buenaventura volcanic field near the Cerro Blanco and La Hoyada volcanic complex.

The depth distribution of earthquakes in the Southern Puna plateau (Figure S5 in Supporting Information S1) are mostly shallow (<15 km depth from the surface based on the  $2\sigma$  boundary) and there are very few middle-to-lower crustal events detected underneath the plateau. However, southeast of the plateau near the Sierras Pampeanas, deep crustal events are more common. In this region, seismicity mostly follows the NE-SW oriented thrust ranges and there is a particularly high number of these deeper events in the ranges surrounding the Fiambala and El Cajon basins. There is also a cluster of events located in the Farallon Negro volcanic complex. The overall event distribution indicates a general trend of deepening of the maximum depths of seismicity approaching the Sierras Pampeanas to the east from the main volcanic arc to the west (see E-W cross-section plots in Figure S7 in Supporting Information S1). A final first-order feature of this catalog is the increase in seismicity between the NW-SE trending Achibarca and Culampaja lineaments and a regional trend of earthquakes that follow the orientation of these lineaments.

## 4.2. Earthquake Magnitudes

Local magnitudes of the earthquake catalog range from  $M_L$  0.1 to 3.9 with a magnitude of completeness of 1.1 (Figure S8 in Supporting Information S1). In general, the events located in the Sierras Pampeanas are of higher magnitude compared to the events on the plateau. However, the largest earthquake of this catalog is located to the north of the Antofagasta basin in an E-W oriented cluster of events. Most of the earthquakes with  $M_L < 1$  are detected near the center of the array. Fitting of the magnitude-frequency distribution to the Gutenberg-Richter equation (Gutenberg & Richter, 1944) gives a  $b$ -value of 1.25 (Figure S8 in Supporting Information S1),

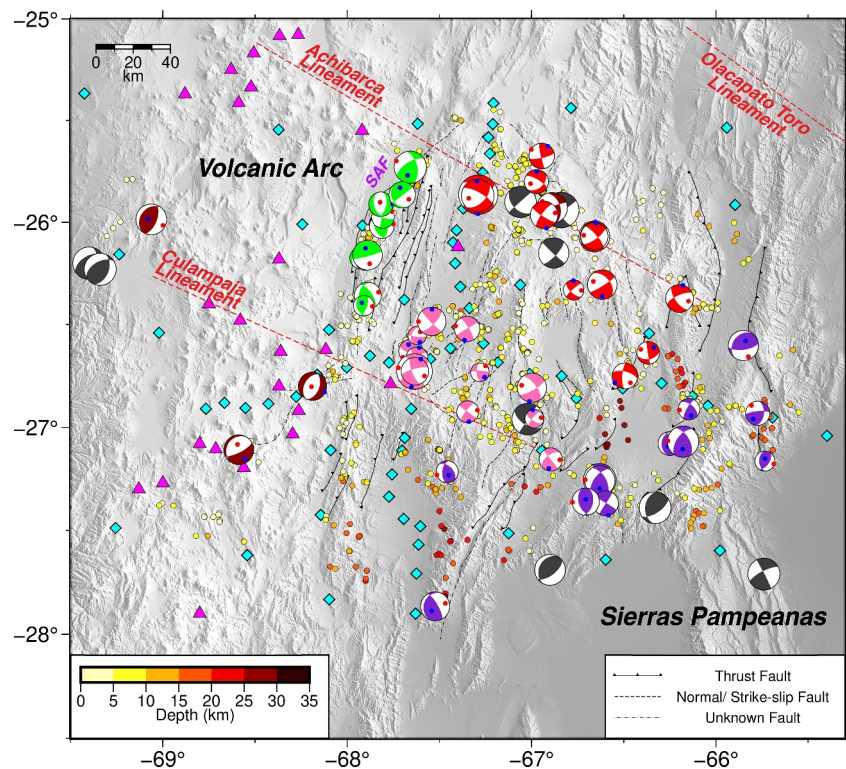


**Figure 5.** Plot of the focal mechanisms of 57 events listed in Table S1 along with 9 focal mechanisms (black) of crustal earthquakes in this region obtained from the Global CMT Catalog (Dziewonski et al., 1981; Ekström et al., 2012). The overall crustal seismicity is plotted in the background color-coded by depth. From the 57 focal mechanisms obtained in this study, 52 events are combined in four groups (Cluster 1: Green, Cluster 2: Red, Cluster 3: Pink, Cluster 4: Purple) for stress inversion. The volcanic events and earthquakes isolated from other focal mechanisms (brown) are separated and not used for the stress inversion. Other symbols are the same as Figure 2.

which is typical for tectonic earthquakes (Frohlich & Davis, 1993). Beneath Cerro Galan, the 10-day earthquake swarm observed in the catalog has a much higher  $b$ -value of 1.85.

### 4.3. Focal Mechanisms

Focal mechanisms are estimated for 57 events which are listed in Table S1. Figure S9 in Supporting Information S1 shows one example event on 26 March 2009 with the P-waveform polarities at different stations and the estimated focal mechanism based on the polarity observations. Most of the events inside the plateau show oblique strike-slip faulting (Figure 5). However, there are some variations in the mechanisms at a local scale. On the NE-SW trending fault system to the east of the Salar de Antofalla, strike-slip faulting occurs to the north on the Acazoque Fault, which transitions to a mixture of normal, reverse, and strike-slip focal mechanisms at the eastern edge of the Salar de Antofalla in the south. In the volcanic fields, the two largest events in the Cerro Galan earthquake cluster exhibit strike slip focal mechanisms, whereas beneath Ojos del Salado volcano and the Buenaventura volcanic field, normal faulting focal mechanisms are observed. To the southeast, strike-slip faulting transitions to reverse faulting events near the Sierras Pampeanas ranges (Figure 5).

### 4.4. Stress Inversion

The stress inversion results obtained from the focal mechanisms indicate an average regional stress field with an E-W oriented  $\sigma_1$  axis, N-S oriented  $\sigma_3$  axis, and vertical  $\sigma_2$  axis in the study area. However, there are local variations in terms of focal mechanisms and therefore inferred stress orientations and relative magnitudes. These subregions are indicated by the focal mechanism groupings on the map in Figure 5, and stress inversion results for each of these subregions are shown in Figure 6.

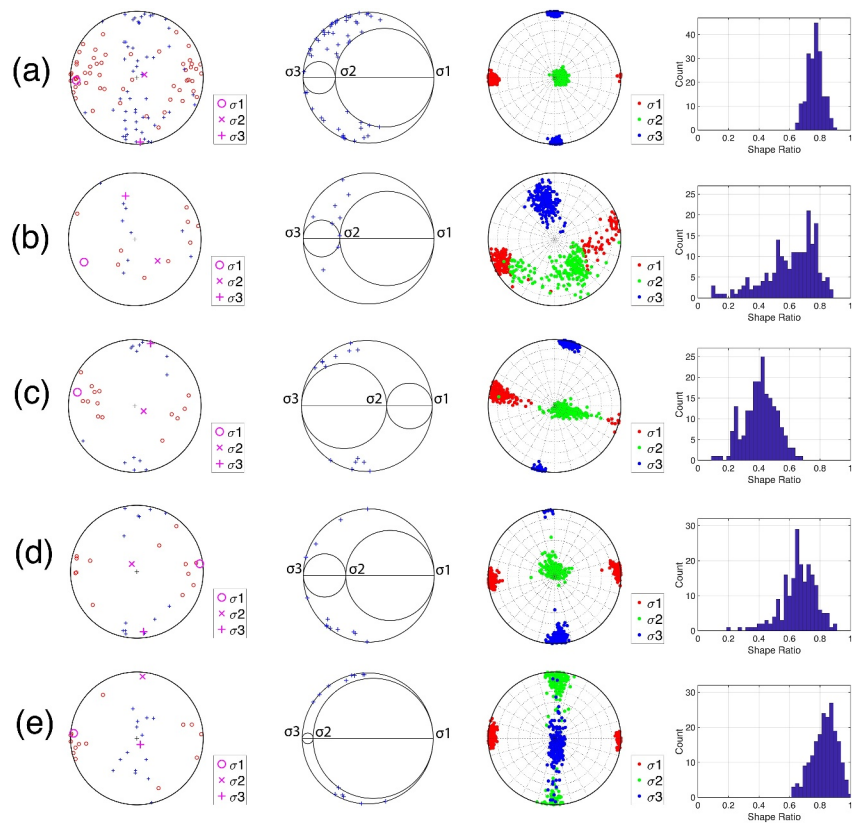


**Figure 6.** Stress inversion results obtained from the focal mechanisms of events in (a) the whole plateau, (b) Cluster 1, (c) Cluster 2, (d) Cluster 3, (e) Cluster 4 as defined in Figure 5. The stress inversion results include (from left to right): principal stress components of each focal mechanism along with a cluster average, relative principal stress values on Mohr circles, locations of principal stress components from the bootstrap resampling analysis, and the distribution of shape ratios obtained from the resampling process.

The cluster of earthquakes in the western part of the study area (cluster 1), near the Salar de Antofalla region, is characterized by a variety of focal mechanisms within a north-south trending zone of seismicity along the eastern margin of the basin. The coexistence of different types of focal mechanisms demonstrates that the principal stress axis directions vary significantly within this region. The dispersion in inferred stress axis orientations and shape ratios for this region is characteristic of regions with low overall differential stress magnitudes and/or abrupt spatial variations in stress orientations. The earthquakes in the central part of our study region can be clustered in two subgroups based on their proximity to the Achibarca and Culampaja lineaments. In cluster 2, in the northern portion of the plateau near the Achibarca lineament (Figure 5), the  $\sigma_3$  direction is well constrained with a NNE-SSW orientation as obtained from the bootstrap analysis. The preferred  $\sigma_1$  and  $\sigma_2$  orientations are ESE-WNW and vertical, respectively, though the partial overlap in orientation estimates for  $\sigma_1$  and  $\sigma_2$  from the bootstrap analysis and low shape ratio of  $0.34 \pm 0.10$  both indicate that the  $\sigma_2$  magnitude is closer to  $\sigma_1$  and much higher than  $\sigma_3$  for this region. In cluster 3 near the Culampaja lineament (Figure 5), there is a well-constrained ENE-WSW oriented  $\sigma_1$  direction, NNW-SSE oriented  $\sigma_3$  direction, and vertically oriented  $\sigma_2$  direction. The Mohr circle representation of the relative principal stress magnitudes and the associated shape ratio of  $0.67 \pm 0.10$  indicate that  $\sigma_1$  is relatively higher and the  $\sigma_2$  magnitude is closer to  $\sigma_3$  than  $\sigma_1$ . In the Sierras Pampeanas region, the prevalence of reverse faulting focal mechanisms produces a consistent stress inversion with an E-W oriented  $\sigma_1$  direction, vertically oriented  $\sigma_3$  direction, and N-S  $\sigma_2$  direction. The shape ratio of  $0.91 \pm 0.08$  obtained from bootstrap analysis suggests that  $\sigma_1$  is much higher than  $\sigma_2$  and  $\sigma_3$  in this region. In addition to the results shown in Figure 6, the bootstrap analysis is repeated with an added noise of  $30^\circ$  as this is the maximum error in the focal mechanisms used for the stress inversion. The results of this inversion exhibit the same principal stress axis direction differences observed between clusters 2, 3, and 4 as those discussed above, demonstrating that these inferred stress

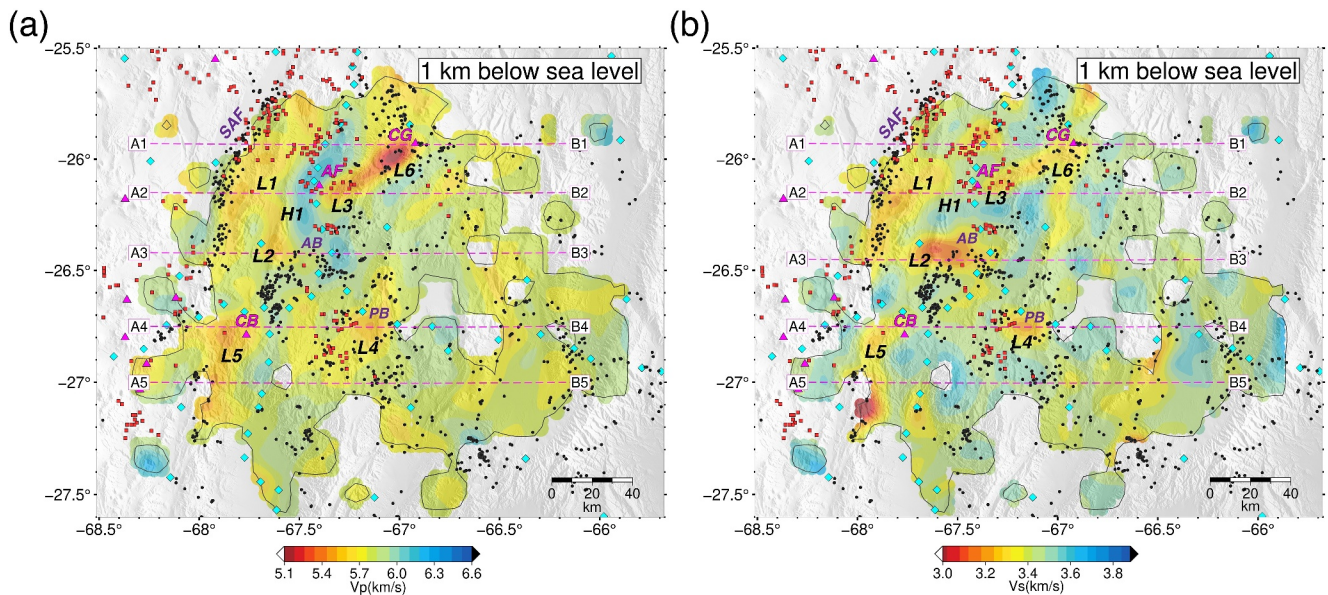


**Figure 7.** Tomography map slices showing (a) absolute P-wave velocity and (b) absolute S-wave velocity 1 km below sea level. In both the maps, the earthquakes obtained from double-difference relocation (black circle) and mafic vent locations (red square) obtained from Grosse et al. (2020) are shown. The black contour line bounds the resolvable area with a  $20 \times 20 \times 8 \text{ km}^3$  size checkerboard. Major high (H1) and low (L1-L6) velocity anomalies are labeled on the figure. Relevant basins (SAF: Salar de Antofalla, AB: Antofagasta Basin, PB: Pasto Ventura Basin) and volcanoes (AF: Antofagasta; CG: Cerro Galan; CB: Cerro Blanco) are labeled for reference. Other symbols are the same as Figure 2.

results are robust and not significantly influenced by uncertainty in focal mechanism estimates (Figure S13 in Supporting Information S1).

#### 4.5. Local Earthquake Tomography

Three-dimensional Vp and Vs models of the study region are produced using travel times from earthquakes located using the VELEST analysis described above. Checkerboard resolution tests are performed to identify the resolvable volumes in the models. Models with checkerboard anomalies of different sizes with 10% positive and negative perturbations from the starting model are used to calculate travel times for the resolution test inversions. Checkerboards with dimensions of  $20 \text{ km} \times 20 \text{ km} \times 8 \text{ km}$  are resolved well horizontally, but vertical resolution is achieved only in the shallowest part of the model. The resolvable volume is calculated by the semblance calculation between input and output models following Zelt (1998). In addition to the initial recovery test, recovery tests using checkerboards shifted horizontally and vertically by half of the checkerboard size are also carried out and the calculated average semblance from all tests above 0.65 is used to define the resolvable volume (Figures S16 and S17; See Supporting Information S1).

In both the Vp and Vs models (Figures 7 and 8), an elongated low-velocity zone (L1) is present along the mountain ranges bounded by a series of parallel faults at the eastern margin of the Salar de Antofalla. Low velocity anomalies are also observed in the Southern Antofagasta basin/Carachi Pampa valley (L2), Northeastern Antofagasta basin (L3), and Pasto Ventura basin (L4). The central Antofagasta basin, however, is associated with an anomalous high velocity anomaly (H1). A low-velocity zone is also present under the Cerro Blanco volcanic complex (L5) and Cerro Galan volcano (L6).

### 5. Discussion

#### 5.1. Comparison of Earthquake Catalogs

The 2,644 well-constrained crustal earthquakes reported in this study are more than a 10-fold increase in detected seismicity compared to Mulcahy et al. (2014), which used the same seismic data set (Figure 3). Many of these events have low magnitudes, however, these low magnitude events provide useful constraints on tectonic interpretations proposed for the region. Furthermore, the improved phase detection in this study from larger events

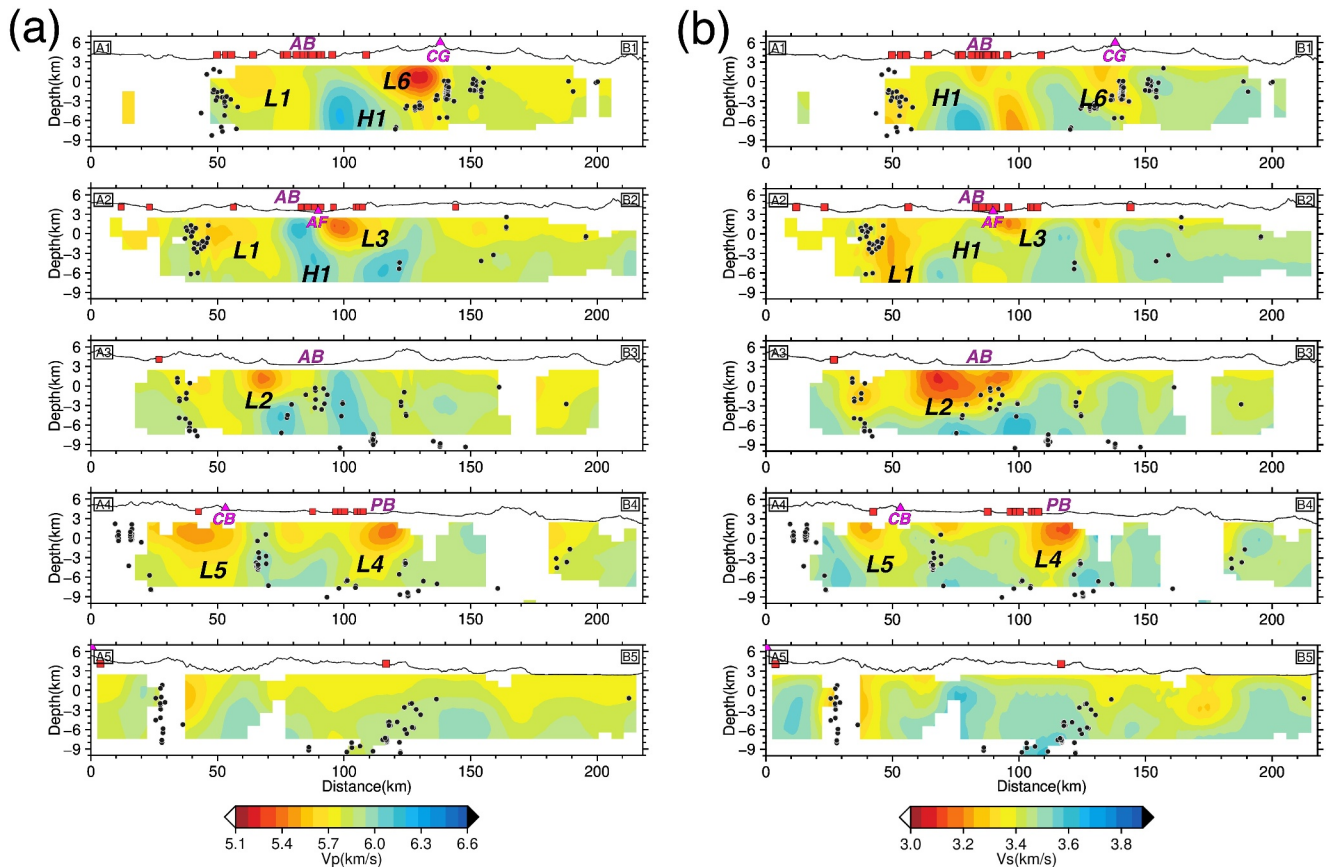


**Figure 8.** Cross-section view of the (a) absolute P-wave velocity and (b) absolute S-wave velocity along five E-W transects as marked in Figure 7. The models show only the resolvable area of  $20 \times 20 \times 8 \text{ km}^3$  size checkerboard tests. Major high (H1) and low (L1-L6) velocity anomalies are labeled. The earthquakes obtained from double-difference relocation (black circle) and mafic vent locations (red square) from Grosse et al. (2020) within 5 km of the cross-section lines are projected on the plots. Major basins and volcanoes relevant for interpretation are marked similar to Figure 7.

allows for 57 focal mechanisms to be well-constrained in the current study compared to 17 in Mulcahy et al. (2014). Where there is overlap, the focal mechanism results of the current study generally agree with those of Mulcahy et al. (2014), as well as from the Global CMT catalog (Dziewonski et al., 1981; Ekström et al., 2012), however, the larger focal mechanism catalog in this study allows for the robust inversion of regional and sub-regional stress orientations and relative magnitudes in the study area as well as placing constraints on the sense of slip of local fault systems when combined with the distribution of seismicity. In addition, magnitudes are reported for all 2,644 well-constrained events in the current study compared to only 17 reported magnitudes in the catalog of Mulcahy et al. (2014). This improved magnitude catalog allows for a b-value analysis of the entire study region as well as the seismic swarm detected under Cerro Galan (see Section 5.5).

## 5.2. Active Faults in the Southern Puna Plateau and Northern Sierras Pampeanas

Most of the seismicity in the Southern Puna plateau is very shallow and limited to the top 15 km ( $2\sigma$  boundary) of the crust below the surface (Figure S5 in Supporting Information S1). This depth distribution of seismicity is similar to other locations on Earth with relatively high heat flow and felsic lithologies (e.g., Hauksson & Meier, 2019; Sibson, 1982), and likely represents a relatively shallow brittle/ductile transition. Though both the current study and Mulcahy et al. (2014) observe a peak in seismicity above 4 km depth below sea level, the second peak in seismicity observed below 10 km depth in Mulcahy et al. (2014) is not present in the results of the current study and instead a smooth decrease in seismicity with depth is observed (Figure S5 in Supporting Information S1). Deeper crustal events are detected mostly in the southeastern part of the plateau, approaching the Sierras Pampeanas fold-and-thrust belt and the Chilean-Pampean flat slab region to the south. In these flat slab environments, it has been argued that a thick thermal lithosphere and an anhydrous lower crust with decreased crustal

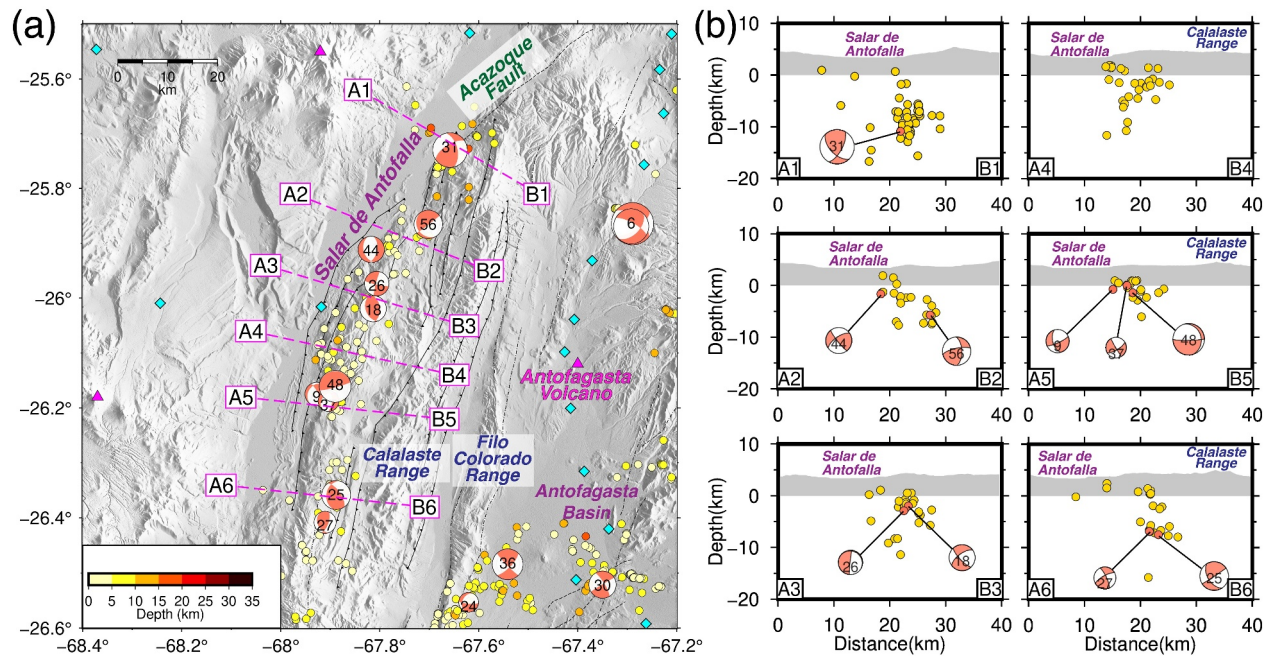


**Figure 9.** (a) A sub-regional map near Salar de Antofalla, overlain with seismic stations (blue diamond), located earthquakes (color coded by depth) and focal mechanisms. (b) Cross-section plot of the earthquakes (yellow circles) and focal mechanisms along six transects marked in (a). The number on the focal mechanisms indicates the event ID in Table S1.

temperatures due to a lack of corner flow in the mantle provides the conditions necessary to promote the occurrence of these deep crustal earthquakes (Devlin et al., 2012).

### 5.2.1. Antofalla and Antofagasta Regions

The Salar de Antofalla is a large, linear shaped basin located directly east of the main volcanic arc of the Central Volcanic Zone. There exists a series of NE-SW trending faults parallel to the salar bounded by the Acazoque strike-slip fault to the north. This region has undergone Eocene-Oligocene shortening, followed by mid-Miocene to Pliocene extension, and a return of E-W shortening in the Pliocene-Quaternary (Marrett et al., 1994; McMillan et al., 2022; Tye et al., 2022). It has been argued that these oscillatory deformation styles are related to lithospheric delamination (Tye et al., 2022). Most of the earthquakes in this region are located within 15 km of the salar and near the Acazoque fault to the north. These events are primarily distributed near the surface traces of NE-SW oriented reverse faults within the range to the east of the salar. The distribution of earthquakes in the cross-section plots (Figure 9) show small earthquake clusters with a range of orientations, however, there is a general trend of seismicity deepening toward the east within this area. Locations of these events match with the dip directions of mapped reverse faults in this region (McMillan et al., 2022). Further north, the cluster of seismicity near the Acazoque fault has a near-vertical orientation. Focal mechanisms from this salar region exhibit a mixture of normal, reverse, and strike-slip fault types unlike the reverse only focal mechanisms reported in Mulcahy et al. (2014). In the northernmost region near the Acazoque fault, one earthquake has a strike-slip focal mechanism (event 31; see Table S1 in Supporting Information); assuming a NE/SW fault strike orientation, this event indicates right-lateral strike-slip motion, which agrees with field observations of the Acazoque fault (Marrett et al., 1994). The focal mechanism also aligns with the near vertical fault plane observed from the cluster of seismicity. The observation of reverse faulting focal mechanisms east of the Salar de Antofalla aligns with geologic observations which suggest a Pliocene-Quaternary return of E-W shortening in this region (Marrett et al., 1994; McMillan et al., 2022; Tye et al., 2022), however, the presence of additional normal and strike-slip faulting in this region suggests a complicated local stress field that will be discussed in a later section. To the east of the Salar de Antofalla region, the Calalaste range and the Antofagasta basin adjacent to the Antofagasta volcano have few detected earthquakes. The lack of earthquakes to the east of the Calalaste range and Filo Colorado range agrees with the geologic observation of deformation being limited to the western side of the Calalaste range (McMillan et al., 2022).

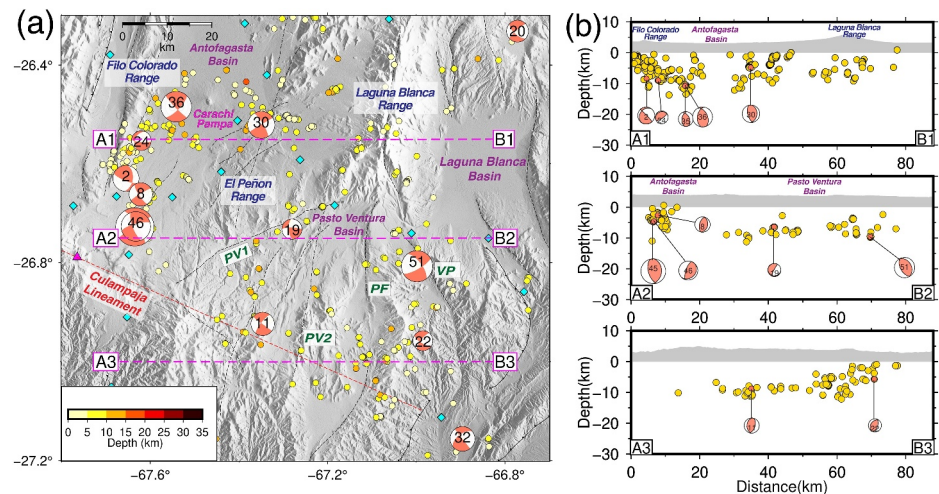


**Figure 10.** (a) A sub-regional map of the central Basin and Range region, overlain with seismic stations (blue diamond), located earthquakes (color coded by depth) and focal mechanisms. Major faults (PV1, PV2: Pasto Ventura, PF: Peña Fria, VP: Vicuña Pampa), ranges, basins, lineaments, and volcanoes are labeled on the map. (b) Cross-section plot of the earthquakes (yellow circles) and focal mechanisms along three transects marked in (a). The number on the focal mechanisms in map view and cross-sections indicates the event ID from Table S1.

### 5.2.2. Central Basin and Range Region

The central part of our study area consists of several earthquake clusters adjacent to basins segmented by uplifted ranges (Figure 10). Though many of these clusters have trends that are parallel to the NE/SW strikes of mapped faults, the overall density distribution of seismic events suggests that these faults host most of the seismicity where they intersect the NW/SE trending Culampaja lineament. The general distribution of events and focal mechanisms in this area agree with Mulcahy et al. (2014), however, the higher number of earthquakes and focal mechanisms in this study makes it possible to relate the seismicity to individual fault systems. Many of the earthquakes to the south of the Filo Colorado range occur in NE/SW trending clusters suggesting that the events occur on the NE-SW striking planes of the focal mechanisms, which would be consistent with right-lateral strike-slip faulting. Similarly, to the east, in the El Peñon region, earthquakes are mostly oriented along the parallel NE-SW oriented faults and right lateral strike-slip motion fits with the observed focal mechanism in this region, as well as geological constraints from offset of young geomorphic features on these fault systems (e.g., Allmendinger et al., 1989). In contrast, earthquakes in the Carachi Pampa valley in between these two regions do not follow any prominent mapped faults. These events are generally lower magnitude and deeper than those in the adjacent ranges. The cluster orientation and focal mechanism of event 36 to the south of Carachi Pampa volcano suggests left-lateral strike-slip motion on a NW-SE oriented fault. This, combined with the lack of a fault trace surface expression, may indicate that this seismicity is associated with slip on new and immature faults. However, Carachi Pampa being an active mafic volcano, these events can also represent low-magnitude volcano-tectonic events caused by the local stress field of the magmatic system.

Previous studies in the Pasto Ventura region (e.g., Allmendinger et al., 1989; Zhou et al., 2013) identified several normal and strike-slip faults which are either newly formed in the Quaternary period or reactivated in transtension from pre-existing pre-Quaternary reverse faults (e.g., PV1 and PV2 in Figure 10). Some of the events align well with these reactivated faults and may represent N-S extensional deformation through right-lateral strike-slip faulting (Event 11). However, there are some earthquakes in between these faults which most likely occurred on small-scale newly-formed faults (e.g., Event 19). To the east of the basin, a few events are located on the Peña Fria and Vicuña Pampa fault systems (Figure 10). Given the NW/SE orientation of the Vicuña Pampa fault system, the focal mechanism from event 51 near this fault indicates left-lateral strike-slip motion which agrees with the surface displacement of the Vicuña Pampa volcanic center (Allmendinger et al., 1989). These events continue to the Laguna Blanca region to the north. The Laguna Blanca basin is surrounded by N-S oriented parallel faults, but most of the earthquakes are located on the Laguna Blanca range at the western margin of the basin.

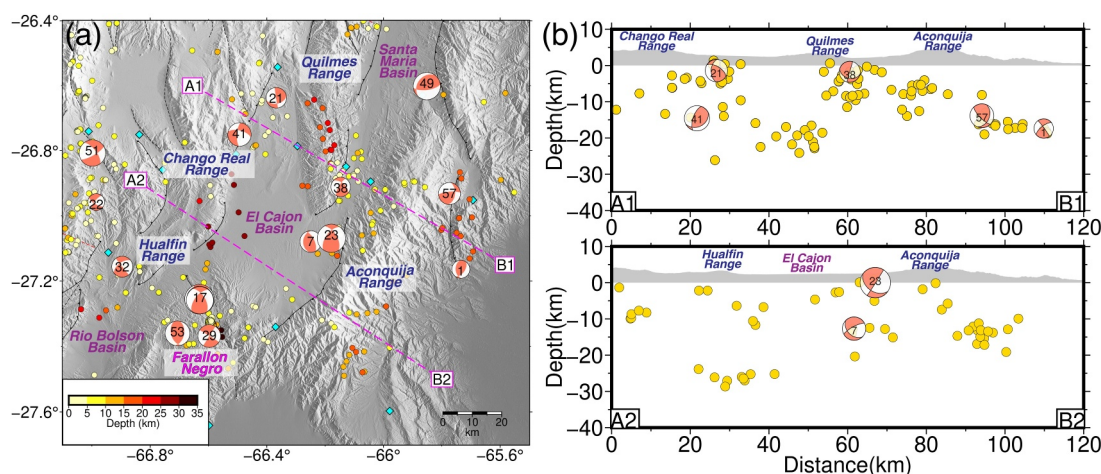


**Figure 11.** (a) A sub-regional map of the Sierras Pampeanas region overlain with seismic stations (blue diamonds), located earthquakes (color coded by depth) and focal mechanisms. (b) Cross-section plot of the earthquakes (yellow circles) and focal mechanisms along two transects marked in (a). The number on the focal mechanisms in map view and cross-sections indicates the event ID from Table S1.

### 5.2.3. Sierras Pampeanas Region

The Sierras Pampeanas southeast of the Southern Puna plateau is a thick-skinned fold and thrust belt involving basement-cored uplift that is interpreted to have formed as a result of Pampean flat slab subduction (Jordan & Allmendinger, 1986; Ramos et al., 2002). In the northern Sierras Pampeanas next to the plateau, Mulcahy et al. (2014) found some scattered shallow seismicity in this area, with a few deep crustal events particularly in and around the Pipanaco basin to the south (Figure 3). The earthquake catalog obtained in the current study shows significant shallow and deep crustal seismicity adjacent to most of the local ranges in this area that characterizes and demonstrates the activity of the underlying fault structures. The seismicity mostly follows trends parallel to the orientation of the ranges, such as the Sierra de Aconquija (AQR), Hualfin (HR) and Quilmes (QR) surrounding the El Cajon basin. The cross-section plots (Figure 11) along two NW-SE transects indicate that the seismicity is dipping in opposite directions in the western side of Sierra de Aconquija and shallows at ~25 km depth. This observation agrees with the presence of an east-dipping backthrust underlying the Sierra de Aconquija as observed in seismic reflection results (Cristallini et al., 2004). The focal mechanisms (e.g., event 1, 57) observed in this area also align with the east-dipping thrust fault. To the west, a steeply dipping zone of seismicity is observed underlying the Quilmes Range, which is consistent with slip on the steeply dipping plane in the focal mechanism from event 38 and the inferred vergence of the underlying structure as proposed by folding observed in seismic reflection data on the southern plunge of this range (Cristallini et al., 2004). Observations of seismic activity to depths of 25 km throughout this region demonstrate active basement-involved uplift in all of these structural domains, and that the brittle-ductile transition in this region is deeper in comparison with the previously described regions. Moreover, the reverse faulting focal mechanisms, high shape ratio in the stress inversion, E-W maximum compressive stress axis direction, and vertical minimum compressive stress axis direction cumulatively provides quantitative geophysical evidence that this fold-and-thrust belt is accommodating shortening in the direction of plate convergence. Another distinct cluster of events within this subregion is observed in the Farallon Negro volcanic complex which may be related to the mining activities as discussed in Mulcahy et al. (2014).

### 5.3. The Stress State of the Southern Puna Plateau and Northern Sierras Pampeanas

The P and T axis orientations obtained from earthquake focal mechanisms (Figure 5 and Figure S11 in Supporting Information S1) and stress inversion results (Figure 6) with approximately E-W oriented  $\sigma_1$  and N-S oriented  $\sigma_3$  axes within the Southern Puna plateau region demonstrates that this portion of the study area is experiencing N-S extension and E-W compression, which agrees well with the geological observations of orogen-parallel extension since the late-Miocene in the Southern Puna plateau (Allmendinger et al., 1989; Schoenbohm & Strecker, 2009; Zhou et al., 2013). Most of this N-S extension is accommodated primarily by NE-SW and NW-SE oriented strike-

slip faults rather than normal faulting. Many of these strike-slip faults formed during growth of the plateau (E-W shortening and vertical extension) during the late Eocene (Carrapa & DeCelles, 2008) and are being reactivated within the present stress field. The regional stress inversions presented in this study (Figure 6) also quantitatively identify stress field variations within the Southern Puna plateau. A significant difference in stress field orientations and relative magnitudes is observed in the northern and southern sections of the Southern Puna plateau near the Achibarca and Culampaja lineaments, respectively. In the north,  $\sigma_1$  and  $\sigma_2$  have closer magnitudes (low shape ratio), whereas in the south the magnitude of  $\sigma_2$  is much closer to  $\sigma_3$ . This change in the shape ratio does not seem to be controlled by changes in the vertical load (i.e.,  $\sigma_2$ ) when both topography and the depth of seismicity are taken into account (Figure S12 in Supporting Information S1). The sub-regional stress inversion results demonstrate that  $\sigma_1$  and  $\sigma_3$  rotate from being aligned approximately perpendicular and parallel to the orogen in the northern section of Southern Puna plateau, respectively (Figure 6) to being aligned parallel and perpendicular to the direction of Nazca/South America plate convergence, respectively, in the southern section of the plateau (Figure 6). There could be at least two possible explanations for these changes in the stress orientations and shape ratios. There may be an increase in  $\sigma_1$  toward the south that aligns with the plate convergence direction, possibly associated with Chilean-Pampean flat slab subduction. Conversely, there may be a decrease in  $\sigma_3$  in the northern section of the Southern Puna plateau due to the increased effect of the mechanism that drives N/S extension in the interior of the plateau. Of course, a combination of these effects could also be contributing to the changes in stress state observed in the Southern Puna plateau.

In the western section of the study area, the seismicity observed in the Salar de Antofalla region demonstrates the existence of a more complicated stress field than the rest of the Southern Puna plateau or the Sierras Pampeanas and does not show consistent E-W shortening as inferred in previous geophysical (Mulcahy et al., 2014) and field based (McMillan et al., 2022; Tye et al., 2022) studies. When grouping this seismicity together, the stress inversion result from the combination of normal, reverse, and strike-slip faulting shows significant scatter in the  $\sigma$  directions. This scattering is indicative of spatially heterogeneous stress orientations in a region of overall low differential stress. Key additional aspects of this seismicity include the observations that, though there are limited focal mechanisms in this region, the normal faulting events (e.g., events 9, 37, and 44) tend to occur at shallower depths than the reverse (e.g., events 25, 27) and strike-slip faulting events (e.g., event 31), and the spatial coincidence of this region of low differential stress with the plateau margin and eastern edge of the volcanic arc. There are several possible causes of the complex stress field east of the Salar de Antofalla, and these will be considered in the context of other previous studies.

Many previous studies have proposed lithospheric foundering as an explanation for temporal and spatial variations in the sense of slip on the faults in this region (e.g., Schoenbohm & Carrapa, 2015; Tye et al., 2022). So, observations in the current study are first considered in the context of this tectonic framework. In this scenario, removal of a lithospheric block/drip can cause local uplift near the surface and compression at deeper depths in the crust due to middle-to-lower crustal flow (DeCelles et al., 2015; Göğüş & Pysklywec, 2008). The localization of foundering-related deformation may be particularly favored in the presence of pre-existing fault structures and a weak brittle crust. The variation in faulting type as a function of depth noted above could be consistent with lithospheric foundering in which the local stress field associated with this process causes flexure of the brittle crust that locally superimposes stress variations upon the N-S extension/E-W compression observed throughout the rest of the Southern Puna plateau. It should be noted that geologic studies indicate that lithospheric foundering ended in this region during the late Miocene/Pliocene (e.g., Kay & Coira, 2009; Tye et al., 2022) and thus the above interpretation would only apply to a new episode of foundering in this region.

The abrupt transition from the cluster of earthquakes east of the Salar de Antofalla to the broad quiescent zone that extends across the main volcanic arc may also provide insights into the cause of the complex stress field. It may be expected that the hot, partially molten arc crust is weak and easily deformable. These characteristics may lead to the observed absence of seismicity within the main arc and locally reduce differential stresses in the adjacent salar region allowing small along strike and depth stress perturbations to result in different faulting types. However, it should be noted that though the zone of seismic quiescence is locally associated with the main arc in the study area, global earthquake catalogs show that this quiescent zone is actually a continuous feature that extends north into the northern Puna and Altiplano plateau where it broadens to more than 500 km in width (Figure 1). In addition, geodetic observations, though sparse on the plateau, indicate that there is little deformation occurring in the plateau interior (Brooks et al., 2003; McFarland et al., 2017). Therefore, the lack of seismicity observed in the main volcanic arc of the study area may more easily be explained as part of a larger-scale phenomenon associated

with plateau interiors. The lack of upper crustal deformation/seismicity in the plateau interior may be attributed to the presence of a middle to lower crustal weak zone (e.g., a detachment or zone of partial melt) that decouples tectonic stresses and deformation from the shallow crust as has been shown in numerical modeling studies (e.g., Babeyko et al., 2006). If this weak zone also promotes middle to lower crustal flow, then modeling work has also shown that a complex stress field may be expected at the lateral boundary of this flow where both shallow extension and deeper compression can develop (e.g., Royden, 1996). The transition from orogen perpendicular middle-to-lower crustal flow (e.g., Husson & Sempere, 2003) to orogen parallel extension may thus provide a more holistic explanation for the complex stress field east of the Salar de Antofalla.

#### 5.4. Seismic Imaging of Intermontane Basins and Shallow Magmatism in the Southern Puna Plateau

The 3D velocity model from local earthquake tomography in this study shows several high and low amplitude anomalies that are present in both the Vp and Vs models (Figure 7). The models resolve features in the upper crust at higher resolution than previous tomographic studies of this region (e.g., Bianchi et al., 2013; Chen et al., 2020; Delph et al., 2017; Heit et al., 2014; Liang et al., 2014), however, the use of only body waves from local crustal earthquakes inhibit the imaging of the middle-to-lower crustal magma reservoirs observed in previous works. The L1 low-velocity region of the tomography models spatially coincides with a series of NE-SW trending faults adjacent to the Calalaste range to the east of the Salar de Antofalla, and likely represents the expected decrease in seismic velocities associated with this broad damage zone (Chester et al., 1993) that has accommodated different stages of compressional and extensional deformation in the Cenozoic era (e.g., Marrett et al., 1994; McMillan et al., 2022; Tye et al., 2022). Several basin regions on the plateau have low-velocity anomalies due to the presence of sedimentary basin fill. These anomalies include the Carachi Pampa valley/southern Antofagasta Basin (L2), northeastern Antofagasta Basin (L3), and Pasto Ventura Basin (L4). The cross-section plots (Figure 8) show that the highest amplitude of the low-velocity anomalies in the Antofagasta basin (L2 and L3) and Pasto Ventura basin (L4) are confined within 1–2 km below sea level, which places the basin depth at approximately ~4–5 km below the surface. Given the vertical resolution limitations in the velocity models, this basin depth is most likely an over-estimation and should be viewed as an upper bound on the thickness of the basins. It should be noted that the correlation between intermontane basins and low-velocity anomalies is not consistent throughout the study area. Several of these basins contain seismically fast intrusive or extrusive mafic volcanic products related to young basaltic magmatism that would be expected to offset the effects of sedimentary deposits in the velocity models. The central Antofagasta basin shows an anomalous NE/SE trending high velocity anomaly (H1). Several Quaternary volcanic vents are located at the periphery of this anomaly (Grosse et al., 2020; Haag et al., 2019). It has been argued that the general distribution of mafic volcanic vents in this region are associated with vertical pathways from the lower crust/upper mantle to the surface along which mafic melts can ascent without intersecting and becoming incorporated with the large middle/lower crustal magma reservoirs that have been seismically imaged in this region (e.g., Chen et al., 2020; Delph et al., 2017, 2021; Heit et al., 2014; Liang et al., 2014; Risse et al., 2008, 2013). In this context, the high velocity anomaly may represent mafic melt that ascended to the upper crust before stalling due to local structural or stress barriers and then crystallized into a shallow plutonic system. Volcanic vents surrounding this high velocity feature represent mafic magma that avoided this region of upper crustal stagnation.

In the Buenaventura volcanic field, low seismic velocities are observed along with a seismically quiescent zone in the Cerro Blanco and La Hoyada volcanic complex. Petrological analysis suggests the presence of a shallow (<10 km) felsic magma reservoir underneath the Cerro Blanco volcanic complex that fed the recent (~4.2 ka) large eruption of this volcano (Báez et al., 2020; de Silva et al., 2022). Cerro Blanco also hosts an active hydrothermal system fed by the magmatic fluids of this shallow magma reservoir (Chiodi et al., 2019). The low velocities (L5) and the lack of seismicity beneath the Cerro Blanco volcanic complex may both be caused by high temperatures due to the hydrothermal system and the presence of a shallow magma reservoir.

#### 5.5. Cerro Galan Caldera

Cerro Galan is one of the largest calderas in the Andes. This volcano is associated with a major ignimbrite eruption that was accompanied by subsidence of the caldera floor ~2 Ma (Folkes et al., 2011; Francis et al., 1983; Kay et al., 2011; Sparks et al., 1985). Under Cerro Galan, low velocity anomalies (L6) are observed between 1 km below sea level and the bottom of the resolvable model at around 7 km below sea level (Figure 12). Given that the highest amplitude of this anomaly is close to the surface, this anomaly can be interpreted as a near-surface

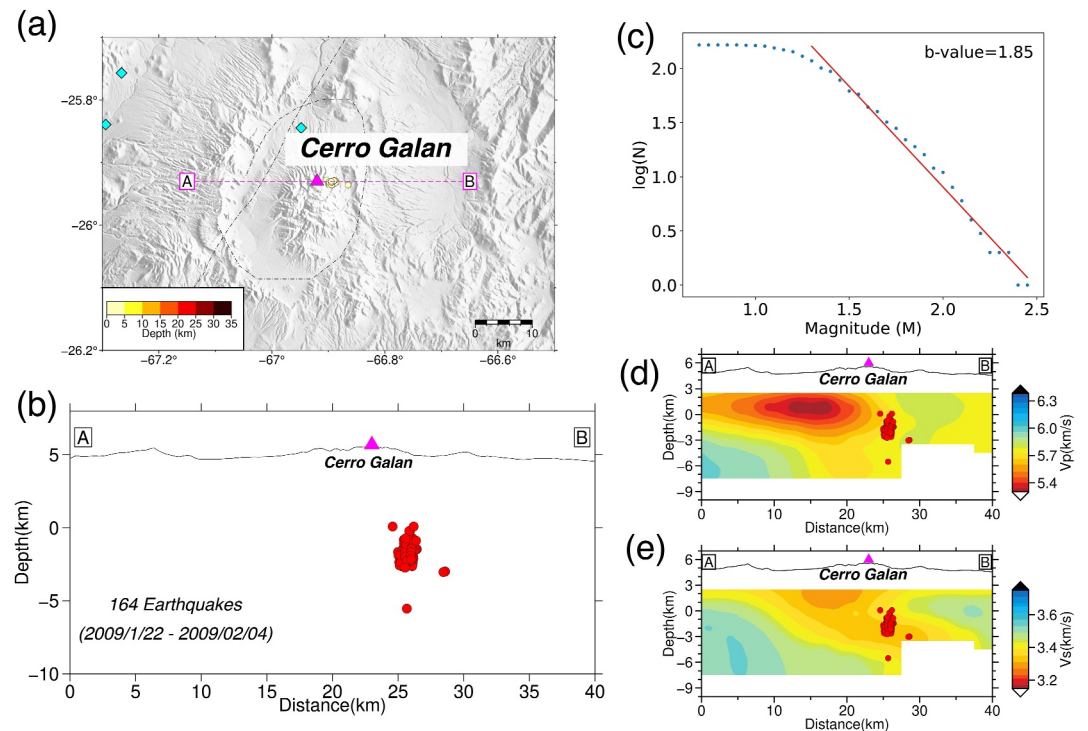


**Figure 12.** (a) Map of Cerro Galan (pink triangle) showing the swarm events (color coded by depth) and nearby seismic stations (blue diamonds). (b) Cross-section view of the swarm events along the A-B line in (a). (c) Fit of the magnitude-frequency distribution to the Gutenberg-Richter equation where the slope indicates  $b$ -value = 1.85. (d) Absolute P-wave velocity and (e) absolute S-wave velocity underneath Cerro Galan from the resolvable tomography model along with the swarm marked as red circles.

hydrothermal system fed by the underlying magma reservoir (Chiodi et al., 2024) or Quaternary deposits inside the caldera. The anomaly is located primarily to the west of Cerro Galan and connects with the low velocity anomaly in the northeastern Antofagasta basin (L3). This observation matches with the pattern of Quaternary deposition between Cerro Galan and Antofagasta volcano as mapped in Schnurr et al. (2006), and therefore the preferred interpretation of the L6 anomaly is the presence of Quaternary deposits. Another important observation from Cerro Galan is the swarm of earthquakes that occurred between 0 and 4 km depth below sea level during a 10-day period (22nd January–4th February) in 2009 (Figure 12). Mulcahy et al. (2014) also identified a few events underneath Cerro Galan during this time frame and reported a 17-hour swarm on 25 January 2009 based on observations on seismic traces, however, most of those events were not well-constrained and not listed in their earthquake catalog. The 164 well-constrained swarm earthquakes detected in this study show a much longer duration and well-defined depth range and allow for a  $b$ -value analysis to be carried out on this swarm. The estimated  $b$ -value of 1.85 is significantly higher than the  $b$ -value for all earthquakes located in this study, as well as the typical  $b$ -value of seismically active regions (Frohlich & Davis, 1993). Earthquake swarms with high  $b$ -values have been associated with the presence magmatic fluids beneath several volcanic regions around the world (McNutt, 2005). The swarm beneath Cerro Galan may indicate that magmatic fluids or hydrothermal fluids migrate into the upper crust from the middle-to-lower crustal magma reservoir previously identified from geochemical analyses (Kay et al., 2010, 2011) and geophysical imaging (Chen et al., 2020; Delph et al., 2017; Heit et al., 2014; Liang et al., 2014; Unsworth et al., 2023). Note that a second earthquake swarm was detected in this seismic data set by Mulcahy et al. (2014) beneath Cerro Torta, though only three of the events in this swarm were well-located. There is also a spatial cluster of events near Cerro Torta in the earthquake catalog of the current study, though these events occur throughout the duration of the seismic deployment and lack the temporal clustering observed for the Cerro Galan swarm.

## 6. Conclusions

In this study, 21 months of broadband and intermediate period continuous seismic data in the Southern Puna plateau is used to constrain the locations, magnitudes, and focal mechanisms of crustal earthquakes within the footprint of the seismic network. Focal mechanisms and magnitudes from this seismicity are used in stress inversions and b-value analyses of the study area. Furthermore, travel times from these events are used for local earthquake tomography to model Vp and Vs in the upper crust. The main outcomes of this study are as follows:

1. This study detects and locates an order of magnitude increase in the number of detected and located crustal earthquakes in the Southern Puna plateau using deep-learning-based phase picking compared to the previous study (Mulcahy et al., 2014) that used the same data set. Local magnitudes of the earthquake catalog range from  $M_L$  0.1 to 3.9 with an estimated magnitude of completeness of 1.1. Focal mechanisms are reported for 57 events in the current study compared to 17 from Mulcahy et al. (2014). The increased number of earthquakes and focal mechanisms allows for local active fault systems to be identified and the sense of slip on these fault systems to be constrained. The increased number of focal mechanisms also enables stress inversion analyses in the study area. Finally, earthquake magnitudes are reported for all 2,644 earthquakes in this study compared to 17 reported magnitudes in Mulcahy et al. (2014). This increase in reported magnitudes makes it possible to carry out a robust b-value calculation of the study area as well as the Cerro Galan swarm.
2. Much of the seismicity in the Southern Puna plateau is characterized by shallow depths (<15 km below the surface) and strike-slip faulting focal mechanisms. Within the Sierras Pampeanas to the southeast, the maximum depth of seismicity deepens and reverse faulting focal mechanisms become dominant on conjugate thrust faults. In both the plateau and the Sierras Pampeanas, the distribution of seismicity tends to align with Quaternary mapped faults and identifies the seismically productive and quiescent fault segments in this region. The western boundary of abundant seismicity in the Southern Puna plateau is directly east of the Salar de Antofalla where a mixture of normal, reverse, and strike slip focal mechanisms are observed. West of the Salar de Antofalla is a seismically quiescent zone that extends throughout the main arc section of the study area, and which is continuous with a larger quiescent zone that extends throughout the Puna and Altiplano plateaus as observed in global earthquake catalogs. This quiescent zone may represent an area where the upper crust is decoupled from large-scale deformation due to a middle-to-lower crustal detachment or zone of crustal flow.
3. A stress inversion of focal mechanisms generally shows N-S extension and E-W compression in the Southern Puna plateau, though regional variations in the stress field are also observed. Between the northern and southern part of the Southern Puna plateau, there is a rotation in the direction of  $\sigma_1$  from an orogen perpendicular orientation to a plate convergence parallel orientation. Accompanying these changes in the stress orientations is a relative increase in the magnitude of  $\sigma_1$  compared to the other principal stresses in the southernmost plateau. These variations in the stress field in the southernmost plateau may suggest an increased influence of plate convergence on the  $\sigma_1$  direction and magnitude near the transition with the Sierras Pampeanas or a reduction in the N-S extensional mechanism operating in the interior of the plateau to the north. Within the Sierras Pampeanas, the stress inversion shows E/W compression and vertical extension characteristic of active crustal shortening accommodated by reverse faulting on oppositely dipping structures. Seismicity east of the Salar de Antofalla includes a combination of normal, reverse, and strike-slip faulting focal mechanisms indicating a complex local stress field. Several mechanisms may explain this complex stress field though its immediate spatial proximity to the seismically quiescent zone to the west may suggest that this stress field is associated with the eastern boundary of east/west oriented middle-to-lower crustal flow.
4. Seismic tomography images the shallow upper crust of the plateau with much higher horizontal resolution compared to previous studies. Several basins in the plateau are identified as low-velocity anomalies. However, this correlation between basins and low-velocity anomalies is not uniform throughout the study area because of the contrasting effects of intrusive or extrusive mafic volcanic products and sediment fill on seismic velocities in these basins. A primary high velocity anomaly in the upper crust occurs in the center of the Antofagasta Basin and is surrounded by Pliocene-Quaternary mafic volcanic vents that previous studies have argued were sourced by asthenospheric melting following delamination of the lower crust/lithospheric mantle. The current study hypothesizes that this high velocity anomaly is the plutonic component of these delamination-sourced mafic melts that stalled in the upper crust due to local stress or structural complexities.
5. Volcanic centers with recent felsic volcanism exhibit shallow low velocity anomalies. The Cerro Blanco anomaly is likely due to the active hydrothermal system in this region whereas the near-surface anomaly observed at Cerro Galan is interpreted as Quaternary fill in the caldera. A 10-day upper crustal earthquake

swarm of 164 well-constrained events with an anomalously high b-value occurred under Cerro Galán which may indicate the presence of magmatic or hydrothermal fluids that have migrated into the upper crust from the middle-to-lower crustal magma reservoir that has previously been imaged in this region.

## Data Availability Statement

This study uses the seismic data from the FDSN Seismic Network X6 (SLIP; Sandvol & Brown, 2007) which is available through Earthscope Consortium Web Services (<https://service.iris.edu/>) and the seismic data from the FDSN network 2B (PUDEL; Heit et al., 2007) which was obtained from the GEOFON Data Centre (<https://geofon.gfz-potsdam.de/>) of the GFZ German Research Centre for Geosciences using the Pyrocko software package (Heimann et al., 2017). For our analysis, we have used PhaseNet (Zhu & Beroza, 2019), REAL (Zhang et al., 2019), VELEST (Kissling et al., 1994), HypoDD (Waldhauser & Ellsworth, 2000), FOCMEC (Snoke, 2003), STRESSINVERSE (Vavryčuk, 2014), and LOTOS (Koulakov, 2009) software packages, which are open-source and available through their individual repositories. The results of this study are fully reproducible using the codes and notebooks archived through Zenodo and available at Mahanti (2024).

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