Structural Characterization of the Taltal Segment in Northern Chile Between 22°S and 26°S Using Local Earthquake Tomography

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Keypoints

- Seismic catalog reveals forearc activity and slab dip variations. Vp anomalies in oceanic plate are associated with mid-depth seismic eventsThe seismic catalog revealed active structures in the forearc, dip changes along the slab and fracturing in the Nazca & South American plates

- Vp/Vs model uncovers oceanic and continental plate anomalies that influence seismicity, including fault systems and hydration changes

- Shallow low Vp/Vs (<1.75) correlate with ore deposits; deep high Vp/Vs (>1.80) suggest fluids and melting for the Lastarria volcanic complex

Abstract

Recordings of earthquakes by a temporary deployment of 88 short period seismometers in northern Chile were used to derive regional 3D seismic velocity models for the Taltal segment. We used the Regressive ESTimator (REST) package for event detection and automatic onset estimation of P- and S-wave arrival times to create an earthquake catalog with 23,985 hypocenters. We followed standard acceptability criteria to create a high-quality dataset and inverted for 3D Vp, Vs and Vp/Vs models using local earthquake tomography.

Plots of hypocenters from the catalog reveal active structures in the upper crust, dip changes along the slab and fracturing within the oceanic crust. The wavespeed models illuminated several features in both the Nazca and South American plate, including the Atacama fault system on the coastline and the Domeyko Fault System in the forearc. These models also provide evidence for fluid circulation caused by the subducting Taltal ridge on the coast and partial melting feeding a volcanic complex close to the Andes. Anomalously low Vp/Vs ratios (<1.77) are associated with copper mining operations in the area, suggesting that this kind of imaging can be used to characterize the distribution of ore deposits in the area.

Plain language summary

We recorded earthquakes in northern Chile with a network of 88 seismometers and used the arrival times of P and S waves to generate 3D wavespeed models of the region. These models reveal several structures in the area, including changes in the angle of the subducting Nazca plate and fractures in the oceanic crust. Among features observed in both the Nazca and South American plates are the Atacama and Domeyko fault systems. We also infer fluid circulation caused by the subducting Taltal ridge and partial melting that is feeding a volcanic complex near the Andes. Low values of the Vp/Vs ratio are associated with copper mining operations in the area and could be used to identify new ore deposits.

Keywords: Northern Chile, 3D Velocity Models, Tectonic Processes, Local Earthquake Tomography, Seismic Catalog, Continental Forearc

1. Introduction

The geologically active margin in northern Chile, where the oceanic Nazca plate subducts beneath the continental South American plate at a relative rate of ~6.0-7.0 mm/yr (DeMets et al., 1990, 1994; Angermann et al., 1999; Norabuena et al., 1999; Sella et al., 2002) offers an ideal setting for seismic investigations of the subduction process in tectonically erosive margins. The lack of anthropogenic noise and the dryness of the soil allow for high SNR recordings of seismic signals. A variety of heterogeneities, such as seamounts and ridges on the oceanic crust, along with the prominent peninsulas along the coast, contribute to diverse modes by which stress in the region is accumulated and released. In particular, a number of studies have focused on the large thrust events in the area, such as the M8.0 Antofagasta earthquake in 1995 (Monfret et al., 1995; Ruegg et al., 1996; Delouis et al., 1997), the M7.8 Tocopilla earthquake in 2007 (Delouis et al., 2009; Peyrat et al., 2010; Bejar-Pizarro et al., 2010), and a proposed Mw~9.5 earthquake (Salazar et al., 2022) 3800 years ago in the Taltal segment between 22°S and 26°S (Figure 1). In the same area, long-term geodetic studies have quantified the degree of seismic coupling (Chlieh et al., 2004; Metois et al., 2013; Metois et al., 2016; Klein et al., 2018) and the capacity of the area to host a large megathrust earthquake (Yañez-Cuadra et al., 2022). Several recent investigations have focused on understanding the sources of seismicity in northern Chile. For example, Mavor et al. (2020) described the kinematics and tectonic evolution of the Taltal Fault, Sippl et al. (2023) used a 15-year seismic catalog to summarize the activity in northern Chile, and Gonzalez-Vidal (personal communication, 2023) deployed a temporary network to explore the relations between heterogeneity in the subducting plate and the degree of interplate locking. In terms of seismic imaging of this zone, Husen et al. (2000), together with Haberland and Rietbrock (2001), set foundations for tomographic analysis by deriving seismic velocity and attenuation models, respectively. However, despite all these studies, the tectonic processes at a regional scale - from the coastline to the volcanic arc - have been largely ignored.

To investigate the roles that features such as a subducting ridge and crustal faults play in the overall tectonics and in the high intermediate-depth seismicity rate of the Taltal segment, we analyzed data from a passive seismic experiment comprising a large network of seismic sensors. The size and the density of this temporary deployment along with the high rate of seismicity in this area (e.g., CSN technical report for the seismicity in Chile 2018, 2019, 2020; www.csn.uchile.cl) facilitates applications of high-resolution imaging using local earthquake tomography (LET). This method uses the arrival times of P- and S-phases generated by local earthquakes to derive 3D seismic velocity models for Vp, Vs and Vp/Vs that highlight the structures and anomalies in the subsurface (e.g., Aki and Lee, 1976; Eberhart-Phillips et al., 1986; Thurber et al., 1995). In this study, we apply this type of analysis to investigate the distribution of fluids in the Taltal segment and its potential relation to the seismic activity between and within the oceanic and the continental, plates (e.g., Christensen, 1996; Moreno et al., 2012; Contreras-Reyes et al., 2021). The large amount of seismic data recorded by this deployment allows us to image the main geological structures and areas of fluid circulation that control the seismic activity at shallow- (<30 km) and intermediate-depth (~100-200 km) in the segment.

2. Tectonic setting

During the past century, only moderate magnitude earthquakes (7.5-8.5) have been documented in the Taltal segment (Figure 1). These include the intraplate M8.0 Calama earthquake in 1950 (Kausel & Campos, 1992), the M7.7 and M7.6 Taltal earthquakes in 1966 (Deschamps, 1980) and 1987 (Ruiz and Madariaga, 2018), the interplate M8.1 Antofagasta earthquake in 1995 (Monfret et al., 1995; Ruegg et al., 1996; Delouis et al., 1997) and the interplate M7.7 Tocopilla earthquake in 2007 (Delouis et al., 2009; Bejar-Pizarro et al., 2010; Peyrat et al., 2010); all of them located in the northern part of the segment (22°S-25°S). Only one documented megathrust earthquake struck the southern part of this region in 1922 (M~8.5, Willis 1929; Abe 1979; Beck, 1998; Comte et al., 2002b; Kanamori et al., 2019), which, due the absence of megathrust events with M>8.5 in the past (Ruiz and Madariaga, 2018) has led to some authors to refer to this portion of the segment (25°S-27°S) as atypical for the Chilean margin. At the same time, the multidisciplinary study of Salazar et al. (2022) inferred that, based on the effects on ancient inhabitants, a large earthquake and tsunami occurred ~3800 yrs ago, suggesting that the area it is capable of hosting large megathrust earthquakes similar to the 2010 Maule and 1960 Valdivia event in other regions of Chile (e.g., Kelleher, 1972; Ruiz & Madariaga, 2018). While megathrusts are infrequent, swarms of seismicity are common in this area (Comte et al., 2002a; Holtkamp et al., 2011; Metois et al., 2016) suggesting that heterogeneities along the plate interface complicate this portion of the Taltal segment.

Offshore, irregularities in the bathymetry of the seafloor such as the Mejillones Fracture Zone (MFZ, Maksymowicz 2015) and the Taltal ridge (Figure 1a) have been proposed to cause a seismogenic segmentation in the region that stops the rupture propagation of local megathrust earthquakes (Maksymowicz, 2015). Pasten-Araya et al. (2021) discussed the presence of a splay fault close to the coastline in the region and emphasized the importance of these types of structures for seismic hazards. Onshore (Figure 1a), the region has two main N-S fault systems, the Atacama fault system (AFS) and Domeyko fault system (DFS), that were formed in response to an oblique transfer of subduction stress (Mavor et al., 2020 and reference therein). The upper-crust is further complicated by several other small geological structures with diverse lineaments and length, such as the Mejillones fault (MF), the Taltal fault (TTF), the Calama-Olacapato-El Toro lineament (COT) and others (Figure 1a; Arabasz 1968; Arabasz Jr, 1971). These lithospheric scale features should play a critical role in the behavior of crustal seismicity and in the distribution of abundant porphyry copper deposits (Cooke et al., 2005; Richards, 2016).

The volcanic arc in this area is shifted towards the east relative to its position to the north and south (Figure 1a), which has been explained by a region of high-density located below the Salar de Atacama (Götze and Krause, 2002; Schurr and Rietbrock, 2004). Eastward, an analysis of electrical resistivity (Diaz et al., 2012; Pritchard et al., 2018; Kühn et al., 2018;

Araya-Vargas et al., 2019) and receiver function studies (Ward et al., 2017; Delph et al., 2017) show two large magmatic bodies, the Altiplano-Puna (APMB) and Lazufre (LMB), are located at the edges of the area of interest, with smaller magmatic bodies in between.

3. Data and Methods

Dataset: The Taltal seismic experiment

The data analyzed in this study were recorded by a temporary network deployed as part of a joint effort between the Advanced Mining Technology Center (AMTC) of Universidad de Chile and the Geophysical Institute from the Karlsruhe Institute of Technology (KIT) of Germany and comprised 84 triaxial short period geophones (3D Geophone HL-6B, 4.5 Hz) and Datacube^3 digitizers sampling at 200 Hz. The instruments covered an area of ~127,000 km^2 and operated between March and October 2020 (Figure 1b).

Seismic catalog and onset detection

The seismic traces recorded by the Taltal experiment were processed using the Regressive ESTimator (REST) automatic picking package described in Comte et al. (2019). REST uses the autoregressive approach of Pisarenko et al. (1987) and Kushnir et al. (1990), combined with data windowing procedures suggested by Rawles and Thurber (2015), to generate detections and onset estimates of phase arrivals. The functions used for detection and onset estimation are indifferent to waveform morphology, relying instead on statistical estimates of similarity and predictability between a subset of samples and a representation of background noise. Hypocenters are determined using a grid search location scheme (Roecker et al., 2004; 2006) with travel times calculated in a wavespeed model specified at a 3D distribution of nodes in a spherical coordinate system.

In this study, we adopted a reference 1D velocity model based on the results of Husen et al. (1999) for shallow and intermediate depths (0-50 km) and IASP91 (Kenneth & Engdahl, 1991) for depths > 50 km. Wavespeeds and travel times are specified on a 3D grid of 157,500 nodes separated by 10 km over an area of 700 x 750 km^2 and 285 km depth.

Events included in the inversion were required to have a minimum of 10 phases and an arrival time residual of less than 2.0 s, resulting in an initial catalog of 23,985 earthquakes with 774,989 P- and 667,114 S-wave arrival times with an overall root mean square (RMS) residual of 0.48 s. In carrying out the LET, we further refine the catalog by applying a stricter selection criterion requiring (1) an azimuthal gap in recording stations of less than 210°, (2) a minimum of 20 total phases, and (3) a maximum residual of 1.5 s. The refined catalog contains 12,851 earthquakes with 415,425 P and 358,770 S arrival times.

Three-dimensional seismic velocity models

The arrival times in the refined catalog were used to generate a 3D velocity model for Vp and Vp/Vs using the joint inversion methodology described in Roecker et al. (2004, 2006). The algorithm parametrizes the subsurface as a volumetric grid in a spherical coordinate system and performs an iterative process that jointly inverts for earthquake locations, Vp, and either Vs or Vp/Vs. The process stops after the reduction in the residual variance becomes statistically insignificant.

The grid has 677,376 nodes spaced at 5 km and covers an area of 540 x 560 km^2 and from the surface to a depth of 270 km. The initial Vp model is the same 1D model used to generate the catalog, and an initial Vp/Vs of 1.77 estimated from a Wadati diagram (Wadati et al., 1933; Kisslinger and Engdahl, 1973; Supporting Information 2) of P and S arrival times. An optimal damping factor is estimated using trade-off curves (Supporting Information 1) of residual and model variance, the latter being defined using the "roughness" parameter of Greenfield et al. (2016). The preferred model is obtained after 16 iterations showing an overall RMS of 0.25 s and a variance of 0.15 s. and residuals (see Supporting Information 3). These values represent a decrease of about 37% in RMS and 45% in variance compared to those from the initial model. Final hypocenters have average arrival time residuals of 0.13 s and 0.79 s for P-and S-wave onsets, respectively. Location uncertainties estimated from marginal probability density functions are on the order of 6 km, 5 km, and 8 km for the east, north and depth coordinates, respectively.

Model Resolution

Based on the results of numerous previous LET investigations, the distribution of events and stations in this study would lead one to expect an overall spatial resolution of structure on the order of tens of km. Nevertheless, the irregular distribution of both stations and earthquakes and the highly nonlinear nature of the inverse problem requires that we document how resolution varies within the model volume. Two common ways to assess the resolution of seismic velocity models are the checkerboard test (e.g., Spakman and Nolet, 1988) and bootstrap resampling (e.g., Calvert et al.,2000; Hicks et al., 2014; León-Ríos et al., 2021). In both cases, synthetic data are calculated in hypothetical models with different sizes and shapes of velocity anomalies. Random noise based on the standard deviation is typically added to the synthetic data to simulate actual data quality (e.g., Hicks et al., 2014; Comte et al., 2019). These synthetic datasets are then inverted following the same procedure as that for the real data and a comparison between the actual and recovered models is made to evaluate resolution scale lengths.

Checkerboard test

The checkerboard resolution tests assumed equi-dimensional anomalies of 15 km, 20 km and 30 km length scale, within which velocities were perturbed by ±5% to form a checkerboard pattern (Supporting Information 4 and 5). Gaussian noise of 1/3 σ of arrival time was added to the synthetic data at a level commensurate with the anticipated uncertainties in the observations, and the result was inverted following the same procedure as that for the actual model. The results for the 15 km dimension anomaly (Supporting Information 4 and 5) show that it is possible to recover the initial perturbations in much of the model volume at this scale. In general, we infer that the data is capable of recovering wavespeed variations at this scale down to 150 km with a geometry consistent with the shape of the subduction margin. Tests performed with smaller dimension perturbations indicate that 15 km anomalies are the smallest size for interpreting possible geological structures.

Bootstrap resampling

The bootstrapping technique is useful to assess the sensitivity of seismic velocity models with respect to the completeness of the event catalog. The bootstrap resampling method suggests that event-based resampling should produce similar results to resampling individual picks (e.g., Calvert et al., 2000; Hicks et al., 2014). We randomly selected 80% of the events in the original data and inverted following the same procedure as for the actual models. Resulting Vp, Vs and Vp/Vs seismic velocity models (see Supporting Information 6) recover most of the anomalies observed in the actual models indicating that the results are insensitive to the event selection criteria. Uncertainties estimated from the bootstrapped resampling are about ±0.025 km/s for Vp and Vs and about ±0.004 for Vp/Vs.

4. Results

Hypocenter catalog

The catalog of well constrained locations has 16,349 events with an average location uncertainty of 6.90 km. Most of the events with depths between 30 km to 120 km depth are located along the subduction interface (slab 2.0, Hayes et al., 2018; Figure 2). Shallow seismicity (<10 km) is associated with the location of mining operations (Figure 2). Earthquakes in the northern part of the model (cross sections P1-P4) are predominantly intermediate-depth (80 km - 120 km depth), while those in the south (cross-sections P5-P8) are more evenly distributed along the plate interface. The northernmost sections (P1 and P2) include upper crustal seismicity that correlates spatially with both the Atacama and Domeyko fault systems, consistent with the active nature of these large-scale systems (Comte et al., 2002b; Bloch et al., 2014; Sippl et al., 2018; 2023). Section P2 also shows a cluster of seismicity at the coast located within the Nazca plate at ~40 km depth that is consistent with the Michilla cluster identified in previous catalogues from Fuenzalida et al. (2013) and Pasten-Araya et al. (2021) after the 2007 Tocopilla earthquake. At greater depths (~80 - 110 km), clusters of seismicity (C1 in Figure 2) are found within the Nazca plate. An additional dense cluster of seismicity evident in section P4 (Figure 2) corresponds to the Jujuy seismic nest (Valenzuela-Malebran et al. 2022). We observe seismicity at shallower depths (<50 km) in section P5 at a distance of ~400 km from the trench that might be related to volcanic activity from either the Lazufre magmatic body or the Altiplano-Puna magmatic body (Ward et al., 2014; 2017). Sections P6 and P7 show offshore clustered seismicity with an NNW trend and a west dipping alignment that reaches down to the plate interface which is consistent with the observations from Gonzalez-Vidal et al. (2023). Similar NNW seismicity lineaments are observed to the north (from profile P4 to P6, Figure 2), which suggests a regional structural pattern in this segment of the margin. In fact, these kinds of seismicity lineaments were previously observed further north by Pasten-Araya et al. (2021), who identified an active offshore splay fault off the coast of Antofagasta. The observed shallow seismicity in profiles P4-P7 suggests a similar active structure to the south of 24°S.

Seismic tomography

First order structures observed in the tomographic models (Figure 3, 4, S7and S8) include the Nazca plate imaged to depths of ~100 km with an east dipping anomaly with Vp ~7.0 - 8.0 km/s and Vs ~4.0 - 4.5 km/s. The South American plate shows Vp values of ~5.0-7.0 km/s and Vs ~3.0 - 4.0 km/s which are consistent with those found in previous investigations (Husen et al., 2000; Haberland and Rietbrock, 2001; Schurr et al., 2006; Pasten-Araya et al., 2021). The average value of Vp/Vs determined with the Wadati diagram (Wadati et al., 1933; Vp/Vs=1.77) is retained in the inversion. We observe a heterogeneous distribution of anomalies in the whole segment with several transition areas from high (Vp/Vs >1.80) to low (Vp/Vs <1.80) ratios observed in both lower and upper plate (Figure 3 and 4). These anomalies and transition areas can be correlated with geological structures observed at the surface, such as the AFS, DFS, the Salar de Atacama, and the Salar Punta Negra (see section z=10 km in Figure 4).

In a closer view of the continental crust, section P1 (Figure 3) shows a heterogeneous velocity structure with Vp ~6.0 km/s in the first 10 km depth and between 6.0 -7.0 km/s at 10 – 30 km depth. The Vp/Vs model shows an anomaly (>1.80; labeled A1 in Figure 4) located at the coastline in the upper crust. Eastward, the model shows a low Vp/Vs patch (<1.74; labeled A2 in Figure 4), that extends along the whole segment at ~69°W from near the surface to 30 km depth (Figure 4). In section P2 the upper crust shows a more heterogeneous forearc between 200 – 300 km from the trench with Vp~6.5 down to 30 km depth and alternating patches with low and high Vp/Vs regions. In particular, the Vp/Vs model illuminates a large high ratio (>1.82) anomaly located at shallow depths which is coincident with the location of the Salar de Atacama. The model also shows transitions from high (>1.80) to low (<1.75) Vp/Vs ratios highlighting the heterogeneity of the segment across the forearc. Continuing to the south, sections P3 to P6 for Vp/Vs show two large patches (A2, A5) with low ratios (<1.75) which are contoured by sub-vertical elongated anomalies (Vp/Vs>1.77) that reach down to the interplate interface. Another unusual vertical-elongated feature appears at 24°-24.5°S, in section P4 and P5, below the Cordillera de los Andes. This anomaly (A6), with Vp/Vs~1.80, is accompanied by shallow seismicity and is coincident with a low resistivity feature identified by other geophysical studies in the area (Diaz et al., 2012; Araya-Vargas et al., 2019).

In the region of the mantle wedge, interplate boundary and subducted plate, P1 shows an area of Vp~8.0 km/s close to the plate interface at 50 km depth that locates above a cluster of seismicity within the Nazca plate. At greater depths (>80 – 100 km), we observe a large (150 km width x 40 km depth) low Vp/Vs (<1.80; labeled A3 in Figure 4) which correlates with the clustered seismicity within the oceanic crust. In section P2, the 8.0 km/s Vp east-dipping-contour shifts upwards in comparison to P1. In this section, at distances >300 km from the trench and at ~50-70 km depth, we find areas with Vp values > 7.6-7.8 km/s that illuminate the mantle wedge that are consistent with values suggested by Comte et al. (2023). In sections P3 to P6, Vp in the lower part of the oceanic plate has a value of 8.2 km/s (labeled A4 in Figure 4). The oceanic slab here has Vp/Vs ratios > 1.82, distinguishing it from the slab in the northern profiles. Sections P6, P7 and P8 show a westward shift of the mantle wedge marked by the Vp~7.6-7.8 km/s contours at a distance about 300 km from the trench. Vp/Vs in the vicinity of the Taltal ridge in sections P6 and P7 (labeled A7 in Figure 4) is low (<1.76). A similar feature, along with the surrounding seismicity, has been described for subducted seamounts in Ecuador (Carnegie ridge; Leon-Rios et al., 2021) and Costa Rica (Husen et al., 2002). Finally, sections P7 and P8 show a large high (>1.80) Vp/Vs anomaly (labeled A8 in Figure 4) that extends for about 100 km in the upper crust.

5. Interpretation and Discussion

Seismic distribution and first-order structures

Our derived 3D Vp, Vs and Vp/Vs velocity models show the structure of the subducting Nazca plate down to 200 km depth (Figure 3 and 4). The upper continental crust has seismic velocities Vp ~5.0 – 7.0 km/s and *Vs* ~3.0 – 4.0 km/s. The continental Moho discontinuity associated with Vp ~7.7 km/s implies a crustal thickness of the South American plate of around 40 – 50 km below the forearc, which is consistent with previous observations (e.g., Husen et al., 2000; Haberland et al., 2001). At a distance of 300 km east of the trench and at depths > ~50 km, we observe the mantle wedge in most of the profiles (see Figure 3).

Below the coastal area, the seismicity shows several clusters that could be associated with regional structural features of the upper and lower plate. Southward from the Mejillones Penisula (P4 to P8, Figure 3 and 4) the seismicity appears to be distributed in lineaments (L1, L2, L3) striking northwest, in concordance with structures observed onshore in the upper plate (Figure 1; Mavor et al. 2020, and references therein), while to the north the seismicity presents a more heterogenous distribution. This change could reflect a latitudinal segmentation of the active structures near the interplate boundary, at least when considering the coverage of our relocated catalog. In particular, P6 and P7 show dense clusters of seismicity offshore, which suggest the presence of west- and eastvergent structures that could be influenced by the Taltal ridge subduction and/or the obliquity of the AFS in the area (Mavor et al. 2020).

At greater depths, we observe two prominent features in the seismicity distribution: (1) intense seismic activity at ~100 km depth that coincides with a low Vp/Vs region (labeled A3 in Figure 4) which collocates with the subducting Nazca plate (P1 to P3 in Figure 3). We note that previous studies have identified Vp/Vs ratios with similar values (Herrera et al., 2018). These reduced Vp/Vs values suggest a more rigid and dehydrated slab prone to a localized increase in intermediate-depth seismic activity. (2) We observe seismic activity at depths between 150 km – 200 km, located mostly at the northern profiles (sections P1-P4). P4 highlights the compressive Jujuy seismic nest (Valenzuela-Malebran et al., 2022). Compared with the Slab2 model (Hayes et al., 2018), our seismic catalog suggests a larger dip of the subducting Nazca plate at depths between 150 km - 200 km in the northern profiles (P1-P4).

Large-scale upper-crust features

The continental crust shows a sequence of low and high Vp/Vs anomalies (Figure 3b). Along the coastal area, and correlating with the AFS, most of the profiles show high Vp/Vs values that could be associated with a more fractured crust due to this fracture zone. This correlation is particularly evident northward of ~25°S (Figure 4). In contrast, the coastal area in the zone of the Taltal ridge subduction is characterized by low Vp/Vs values which could be explained as a change in fluid transport inside the crust above this subducted feature. Coincidently, the structures associated with the AFS show local rotations in this zone (Figure 4). In a similar way, at distances of ~200 km – 250 km from the trench (Figure 3b), we observe another high Vp/Vs zone that coincides with the DFS. We infer that, in most profiles (Figure 3 and 4), this large-scale, seismically active geological structure extends down to ~50 km depth and is associated with the large porphyry copper deposits in the region (Reutter et al., 1996; Tomlinson and Blanco, 1997a; 1997b; Camus and Dilles, 2001). Eastward from the DFS, low Vp/Vs anomalies (A1-A4, <1.80; Figure 3 and 4) may be associated with an ancient magmatic arc that might have metamorphosed the surrounding area (e.g. Diaz et al., 2012) and contributed to the accumulation of porphyry copper deposits (Comte et al., 2023; Chen and Wu, 2020). This observation coincides with the location of large copper mining operations in the area such as Chuquicamata, Gabriela Mistral and Escondida, and suggests that LET technique can be used as a tool to identify and characterize porphyry copper deposits at greater depths. In terms of absolute Vp velocity, and at crustal depths (< 50 km),the DFS is in general correlated with a transition from high Vp to the west to low Vp to the east of this structural limit, which could reflect a west-east thermal gradient related to active magmatic arc and subduction geometry (Contreras-Reyes et al., 2021) and/or the presence of high density basement units related to ancient volcanic arcs westward from the DFS (Bascuñán et al., 2016). The presence of cold and dense basement westward from the DFS is concordant with the more rigid (low Vp/Vs) crust observed between the AFS and DFS (Figures 3 and 4). East of the DFS, Vp/Vs values show a more heterogeneous distribution with higher strength (low Vp/Vs) in the southern portion of the Salar de Atacama basin (SdA) and to the southeast of the Salar de Punta Negra basin (Figure 4). By contrast, higher Vp/Vs anomalies are located to the north of the SdA. This heterogeneous distribution in strength could be related to the variability of the ancient basements in this region (e.g. Niemeyer et al., 2018) and the presence of regional structures, as the northwest Calama-Olacapato-El Toro lineament (COT, Lindsay et al., 2001) that seems to control the strength change between the northern and southern portions of the SdA region (figure 4).

At a regional scale, the succession of different strength bands (roughly north-south) in the forearc correlates well with large scale electric resistivity anomalies observed in magnetotellurics studies of the zone (Slezak et al., 2021; Contreras-Reyes et al., 2021), where crustal low strength anomalies (high Vp/Vs) correlate with low resistivity zones associated with costal large-scale structures (the AFS) and the DFS.

Subducted slab, Mantle wedge and Fluid circulation

First-order observations (sections P3-P7 in Figure 3) suggest a hydrated slab subducting down to ~80 - 90 km depth. At that point, we observe a transition to lower Vp/Vs (<1.76) suggesting a dehydration process consistent with temperature and pressure at these depths (Haberland and Rietbrock, 2001) which leads to a dryer slab at greater depths (>100 km). As mentioned before, the Vp/Vs model (Figure 3 and 4) shows elevated ratios (>1.77) at shallower depths (5 -10 km) that can be associated with the SdA and Salar Punta Negra basins. Moreover, the high Vp/Vs ratios allow us to estimate the in-depth extent of the fluids circulating down to ~30 km depth. At 30 km depth, we observe a predominantly low Vp/Vs region (<1.77) that covers most of the area of study. However, in profiles P7-P8 a high Vp/Vs anomaly (labeled A8 in Figure 4) can be observed. This feature is more prominent at greater depths (~50 km), where we clearly observe a transition to higher values of Vp/Vs (>1.80). We attribute this anomaly to an increase in the fluid circulation promoted by the Taltal ridge, which subducts between 24°S – 25°S. The presence of large-scale, shallow oceanic features can cause basal erosion and fractures in the overriding plate (Scholz and Small, 1997; Contreras-Reyes et al., 2011) enhancing the transport of fluids from deeper to shallower depths (Collot et al., 2004; Marcaillou et al., 2016; Leon-Rios et al., 2021)

Finally, profiles P4 and P5 (Figure 3) show an elongated anomaly (labeled A6) with Vp/Vs~1.79 - 1.80 located at 50 km depth and ~ 300 km from the trench. We interpret this feature as fluids moving upwards from the plate interface towards the surface, promoting partial melting and feeding the northern edge of the LMB and other volcanic complexes (Haberland and Rietbrock, 2001; Diaz et al., 2006; 2012; Araya, 2019). The shallow seismicity observed ~400 km from the trench corroborates the hypothesis of fluid circulation in the area. We note that the SdA area (around profile P3-P4, Figure 4) correlates well with a part of the mantle wedge (depth ≥ 50 km) characterized by high Vp (>8.0 km/s) and low Vp/Vs (<1.70) bounded by low Vp (~7.5 km/s) and high Vp/Vs (>1.80), which suggest a correlation between anomalies associated with high fluid content (and high temperatures) and the active volcanism in the area, including the local eastward migration of the volcanic arc around the SdA.

Conclusion

Data from ~23,000 earthquakes recorded by a large temporary deployment that operated in northern Chile for an 8-month period allowed us to characterize the seismotectonic structure of the Taltal segment in northern Chile. We applied LET to jointly derive 3D seismic velocity models for Vp, Vs and Vp/Vs and earthquake locations. The seismicity occurs mostly along the slab interface but also within large-scale structures in the overriding plate. At greater depths, we observe a change in the dip of the slab that we suggest results from a strong slab-pull. Offshore, we observe clustered seismicity that we interpret as a splay fault that reaches the slab interface. This seismicity appears to be a consequence of the Taltal ridge subducting in the southern part of the region.

The Vp and Vs seismic velocity models illuminate first-order structures such as the oceanic plate and the South American upper-crust. The Vp/Vs model identifies regions which change from reduced (<1.77) to elevated (>1.77) ratios that we interpret as large-scale fault systems that penetrate down to the seismogenic zone. The oceanic slab also shows a transition from elevated (>1.80) to reduced (<1.76) Vp/Vs suggesting a highly hydrated plate at seismogenic depths that dehydrates and evolves into a dryer and more rigid slab at greater depths. The latter might also contribute to explaining the high rate of intraplate seismicity observed at ~200 km depth.

Low Vp/Vs anomalies (<1.75) at shallow depths (<20 km) collocate with sites of large copper mining operations and suggests the use of LET to illuminate locations of porphyry copper deposits. High Vp/Vs anomalies (>1.80) at ~50 km depth suggest circulation of fluids caused by the incoming Taltal ridge that erodes and fractures the southern edge of overriding plate. They also suggest the presence of partial melting associated with the Lazufre Magmatic Body and other small volcanic systems.

Acknowledgments

The authors acknowledge the funding from Fondecyt Postdoctorado 2022, No 322099; NSF-China-ANID PI18003; PIA AFB220002. Alejandro Faundez and Gerardo Peña who assisted in the network deployment. Section profiles and map view figures were made using GMTv5 (Wessel et al., 2013) and colored following the guidelines for CVD accessibility by Crameri et al. (2020).

Data availability

Temporary network details in FDSN database (Andreas Rietbrock, Diana Comte, & Sergio Leon-Rios (2020): Taltal temporary deployment. International Federation of Digital Seismograph Networks. Dataset/Seismic Network. https://doi.org/10.7914/mc8r-ft72). Initial and final models as well as hypocenter catalog, arrival times are available in ZENODO with the DOI 10.5281/zenodo.8271327.

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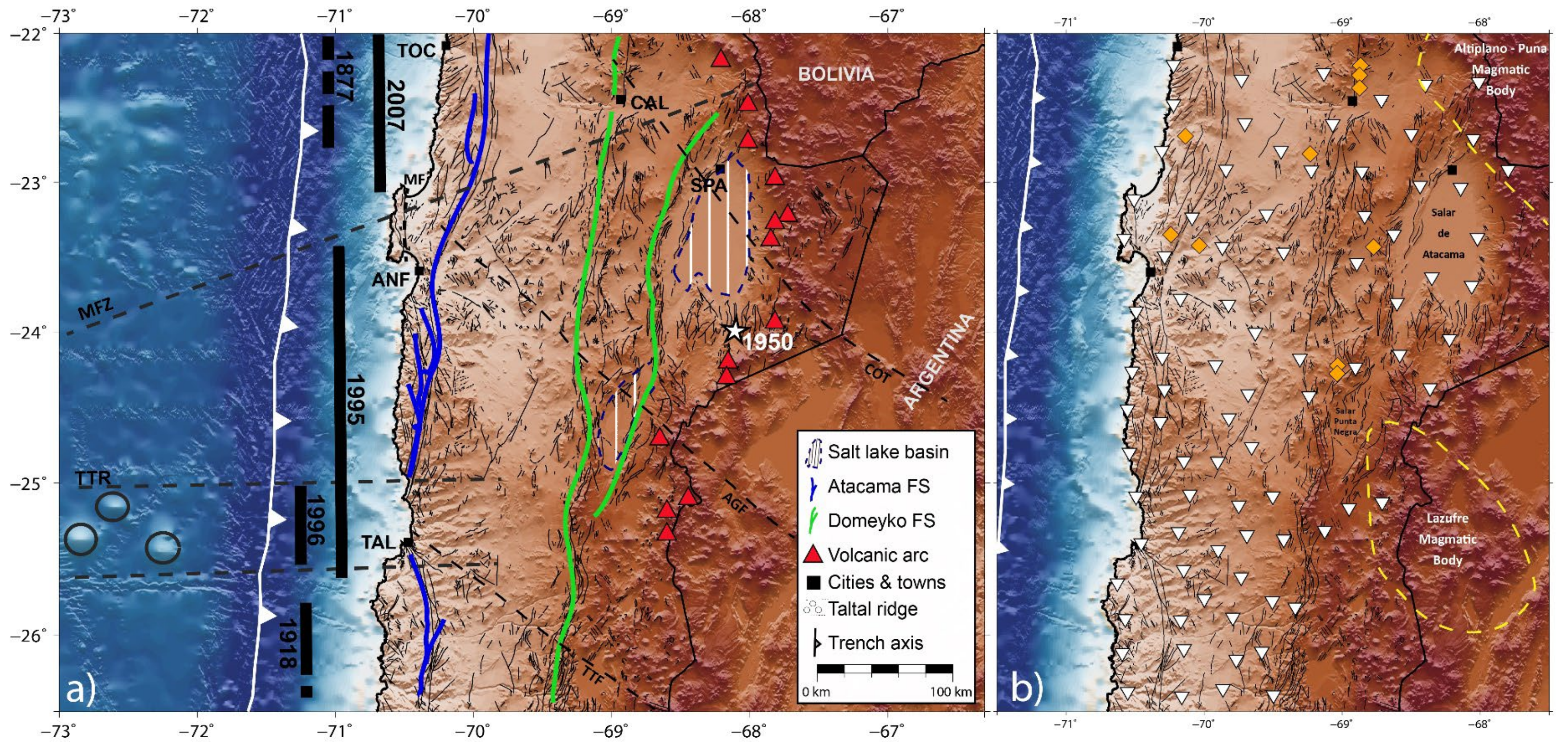

Figure 1. **a)** Seismotectonic setting of the study area. Solid black lines represent the extent of historical megathrust earthquakes in the area (Monfret et al., 1995; Ruegg et al., 1996; Delouis et al., 1997; Delouis et al., 2009; Peyrat et al., 2010; Bejar-Pizarro et al., 2010; Ruiz and Madariaga, 2018) and white star show the epicenter of the intraplate 1950 Calama earthquake (Kausel and Campos, 1992). Solid blue and green lines mark the main trend of the Atacama and Domeyko Fault Systems, respectively. Segmented black lines represent crustal faults: COT, Calama-Olacapato-Toro; AGF, Achibarca-Galan fault ; TTF, Taltal fault; MF, Mejillones fault. Red triangles show the active volcanoes and segmented lines offshore indicate the projection of the Mejillones Fracture Zone (MFZ) and Taltal ridge (TTR). Black squares highlight major settlements in the region, TOC: Tocopilla, CAL: Calama, SPA: San Pedro de Atacama, ANF: Antofagasta, TAL: Taltal. **b)** Distribution of the temporary seismic experiment with 88 short period 4.5 Hz geophones (white triangles) recording at 200 sps. The network collected data for 8 months, between March and October 2020. Yellow squares indicate major mining operations in the area. Black squares represent settlements in the region.

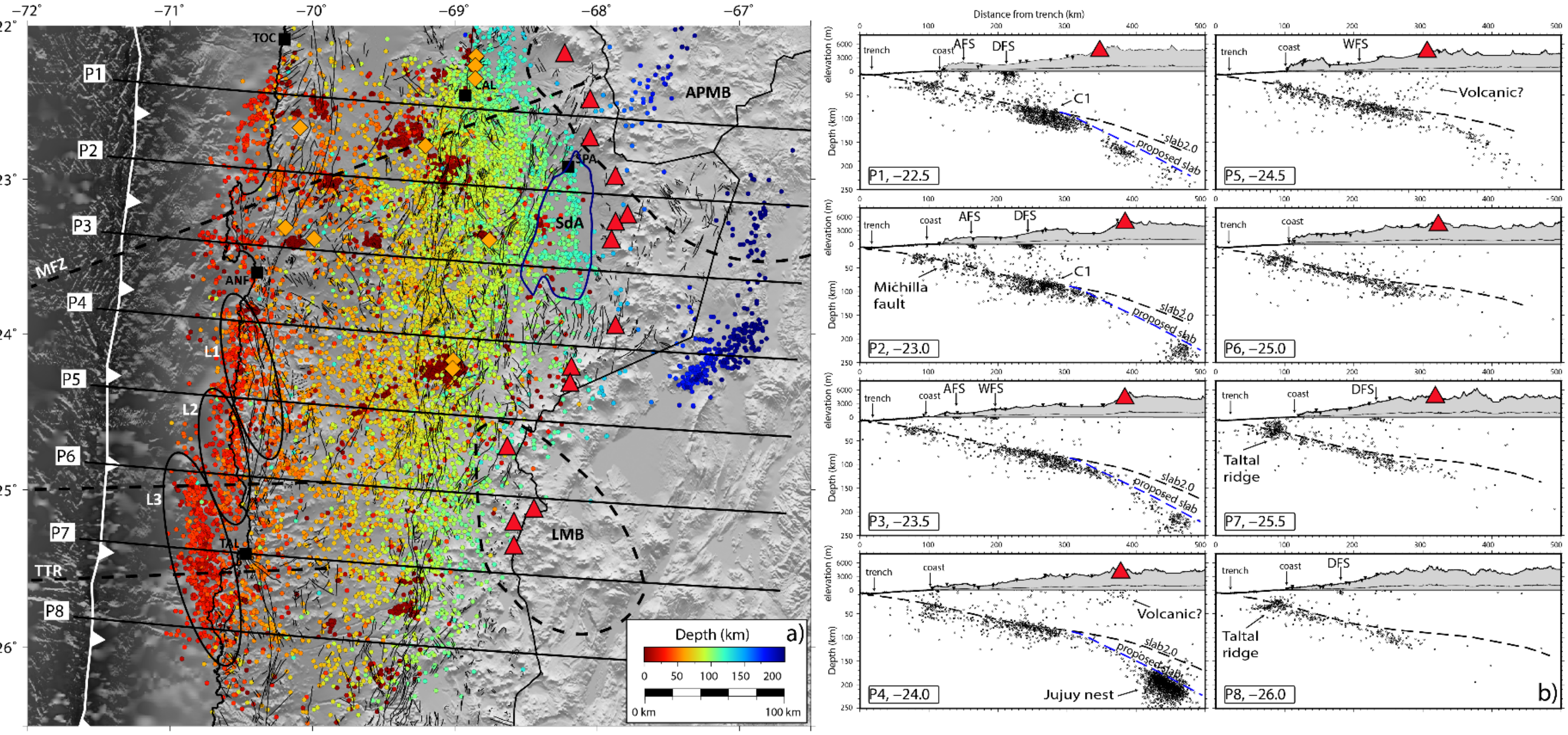

Figure 2. Seismicity distribution for the Taltal segment. **a)** Map view with earthquakes as small circles colored according to depth. Yellow squares indicate major mining operations in the area. Red triangles represent the active volcanic arc. The ellipses show the Norwest lineaments L1, L2, L3 described in text. Black squares show the main settlements. MFZ: Mejillones Fracture Zone, TTR: Taltal Ridge, APMB: Altiplano-Puna Magmatic Body, LMB: Lazufre Magmatic Body, SdA: Salar de Atacama. **b)** W-E profiles with the seismic distribution in depth as shown in scale. Inverted triangles represent the station distribution in the area. The volcanic arc is represented by red triangles. AFS: Atacama Fault System, DFS: Domeyko Fault System.

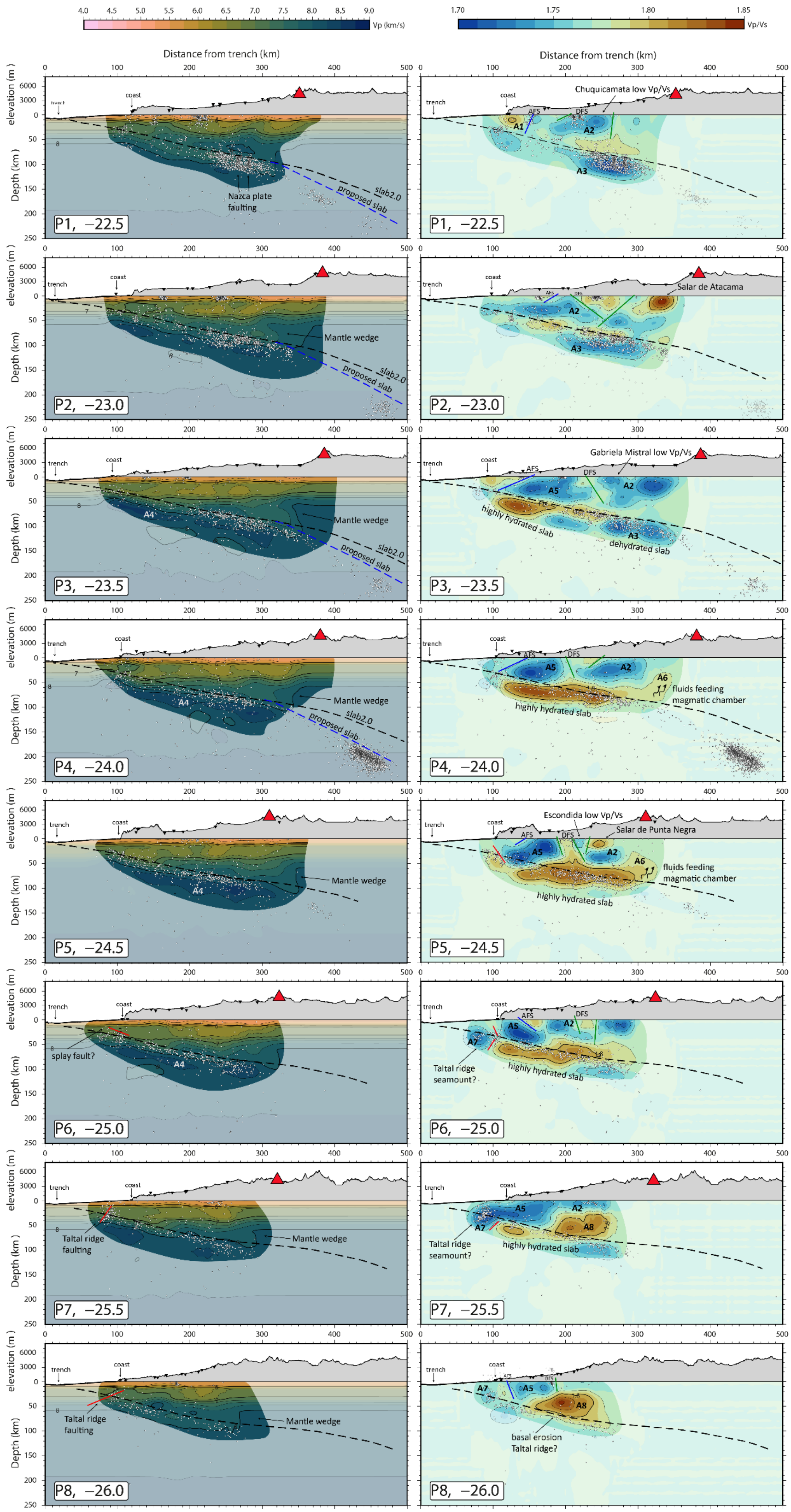

Figure 3. Cross sections of the 3D velocity model for Vp **(left)** and Vp/Vs **(right).** Results are shown along 8 W-E profiles shown in Figure 3. Vp velocities and Vp/Vs ratios are color-coded and isocontours are plotted every 0.25 km/s and 0.05 for Vp and Vp/Vs, respectively. Well-resolved areas are highlighted based on the resolution tests. Width for projection of hypocenters and stations is 20 km. Relocated hypocenters are plotted as white circles, and stations are represented by inverted triangles. Proposed slab interface (see text for further details) is represented by segmented blue line while slab 2.0 (Hayes et al., 2018) is shown with segmented black line. Red triangles indicate the position of the volcanic arc. AFS: Atacama Fault System, DFS: Domeyko Fault System; A1-A8, anomalies described in text.

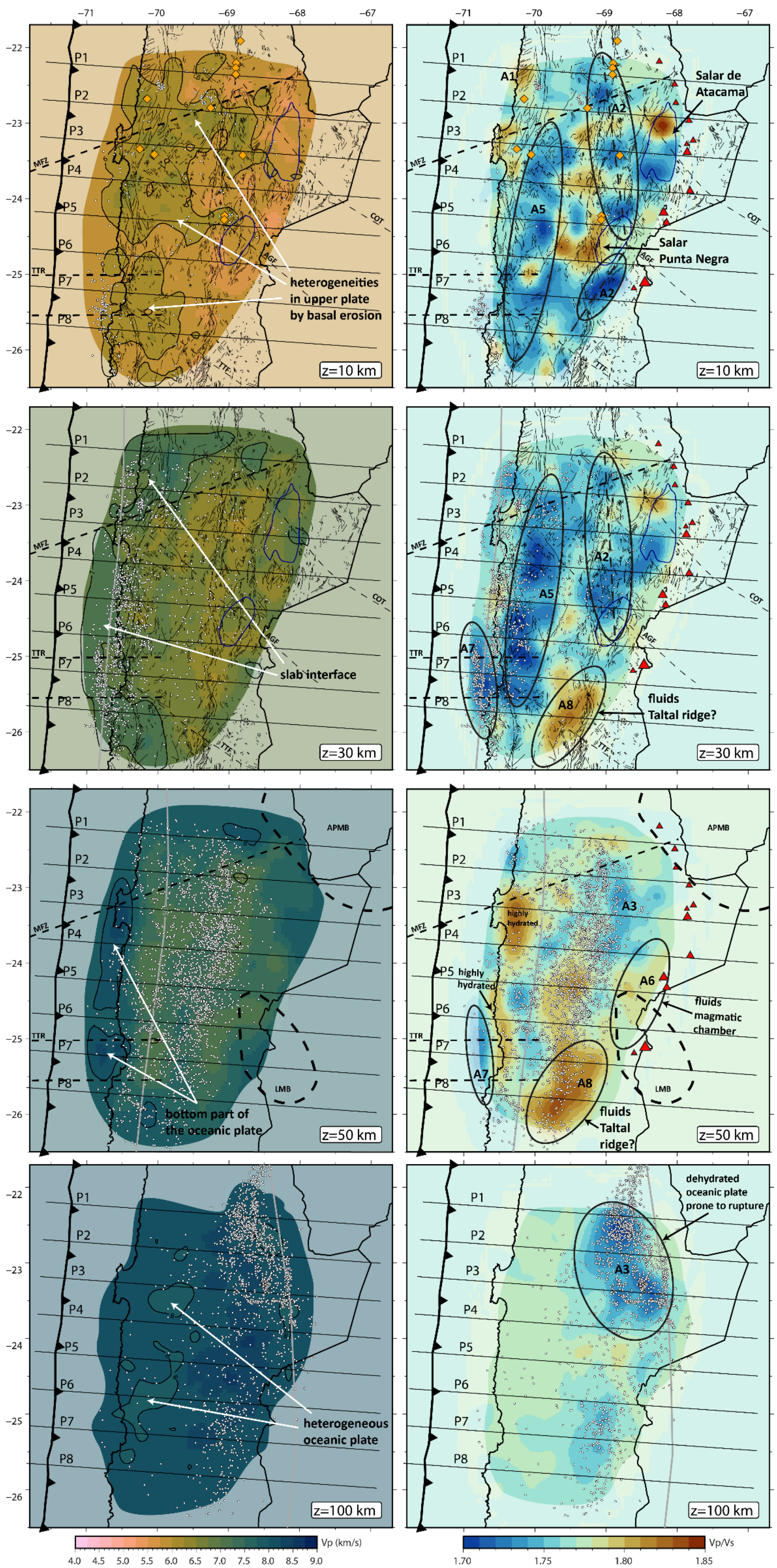

Figure 4. 3D velocity models, Vp **(left)** and Vp/Vs **(right)** shown in horizontal slices at 10, 30, 50 and 100 km depth. Well-resolved areas are highlighted based on the resolution tests. Red triangles indicate the position of the volcanic arc. Major mining operations are represented by yellow squares in the 10 km depth slices. Velocity anomalies collocated to surface observations and cities in the text are also shown in the 10 km depth slice. Location of cross section profiles of Figure 3 are shown as black solid lines. Corresponding slab depth contour (Hayes et al., 2018) is represented by a thick gray line. Seismicity is plotted by depth, d, with d ≤ 10 km in z = 10 km, 20 < d ≤ 35 km in z = 30 km, 40 < d ≤ 55 km in z = 50 km, and 90 < d ≤ 110 km in z = 100 km. Fault map is plotted at shallower depths (10-30 km). MFZ: Mejillones Fracture Zone, TTR: Taltal Ridge, APMB: Altiplano-Puna Magmatic Body, LMB: Lazufre Magmatic Body. The anomalies labeled A1-A8, are described in the text.