Analysis of the Magmatic – Hydrothermal volcanic field of Tacora Volcano, northern Chile, using Travel Time Tomography

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A. OVERVIEW

Seismic tomography in volcanic-hydrothermal systems

1. It allows to infer the hydrodynamic state beneath the volcanic building and the surrounding areas.
2. Locate spatially the magmatic reservoirs and related alterations.
3. Different petro-physical parameters of the host rock such as temperature, composition and density, can be linked to the 3D velocity structure of P- and S- seismic waves.
4. Locate the extraction zones of geothermal energy.

B. GEOTHERMAL EXPLORATION IN NORTHERN CHILE

The **southern segment of the Central Volcanic Zone**, in northern Chile, has been the focus of increasing attention due to the **large number of hydrothermal systems**. In this zone, there are about 90 geothermal areas, of which only a few are under systematic exploration. Particularly, **Tacora volcano (17°43'S – 69°46'W)** (Fig. 1) has been studied during the last years due to the presence of active **thermal manifestations. Hot springs, fumarolic fields,** and the presence of extensive areas with **hydrothermal alteration**, suggest that it could correspond to a promising geothermal field.

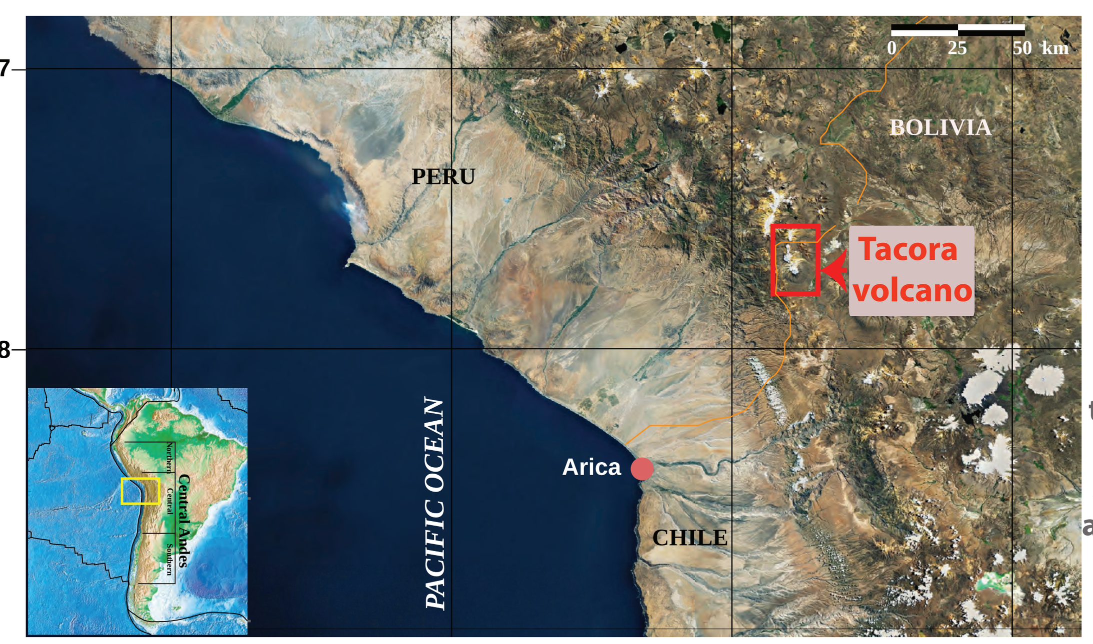


FIGURE 1

Digital elevation model showing the regional context of Tacora volcano. An inset is showing an overview of South America

C. TACORA VOLCANO

Tacora Volcano (Fig. 1 & 2) is a **composite stratovolcano** located at ~100 km northwest of Arica, northern Chile region. It has a **summit elevation of 5980 m a.s.l., and 1700 m from its base.** Andesite samples indicate an **age range from 0.489 ± 0.015 Ma to 0.363 ± 0.007 Ma,** corresponding to the **Middle Pleistocene** (1). The last explosive activity of the Tacora volcanic system is probably related with an explosion crater about 500 m in diameter, located on the NW side of the volcano. Presently, **permanent fumarolic degassing characterizes the upper portion of the NW and W flanks and weak degassing occurs on the volcano summit** (2,3).

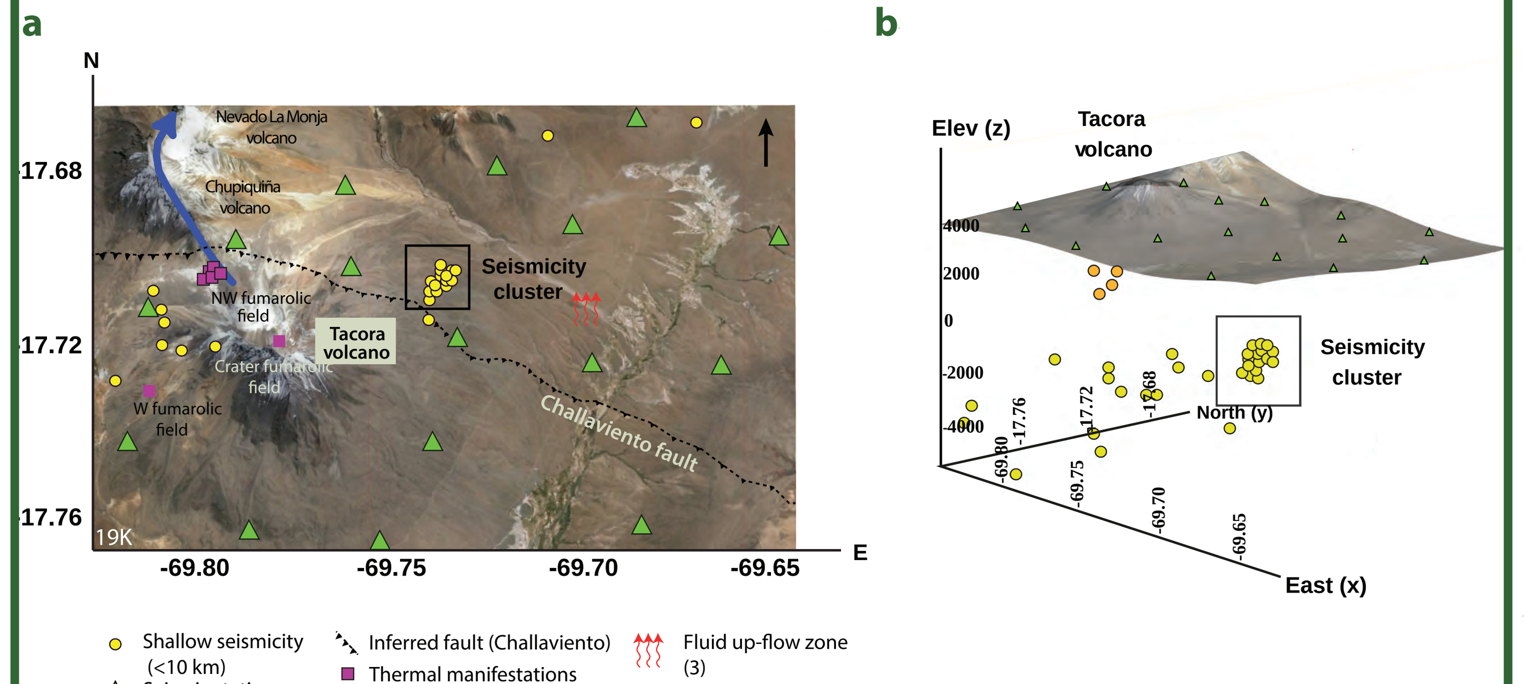


FIGURE 2

Local map of Tacora volcano and the surrounding area showing the seismic network coverage

Final hypocenters of local seismicity beneath Tacora volcano are shown in a 3D view. A shallow cluster is boxed in both figures

Beneath Tacora volcano is located the **Challaviento reverse fault** (Fig. 2) that belongs to the **Incapuquio - Challaviento fault system** of Middle Eocene age. The Incapuquio – Challaviento fault system (ICFS) is exposed northwestward through Peruvian territory (3,4). The southeastern prolongation in Chile is covered by younger volcaniclastic units (Oaxaya and Visviri Formations; Oligocene - Pleistocene) and the previously mentioned volcanic units and deposits. This system, of **WNW-ESE orientation**, is mainly composed by **two reverse faults**, Incapuquio and Challaviento, and other secondary structures. The ICFS includes **also subvertical faults and currently is seismically active in Peruvian territory** . So far, no research was done regarding its seismic activity in Chile.

D. SEISMIC TOMOGRAPHY: VELOCITY MODELS

A **seismic network of 17 short period, three-components, and continuously recording seismic stations** was deployed in the area of Tacora volcano (Fig. 2) from August to December 2014. **The coverage area was 20 x 15 km²** . The body wave data set consisted of **P- and S- arrival times from about 1000 events**. Earthquakes recorded by at least 10 stations and with predicted arrival times using the 1D model within an initial outlier residual threshold of larger of 2 s and 10 per cent of the total travel time were selected. Application of these criteria resulted in a **reference data set of 7413 P- and 7269 S- wave arrival times.**

Vp/Vs and ΔVp/Vp (%) models

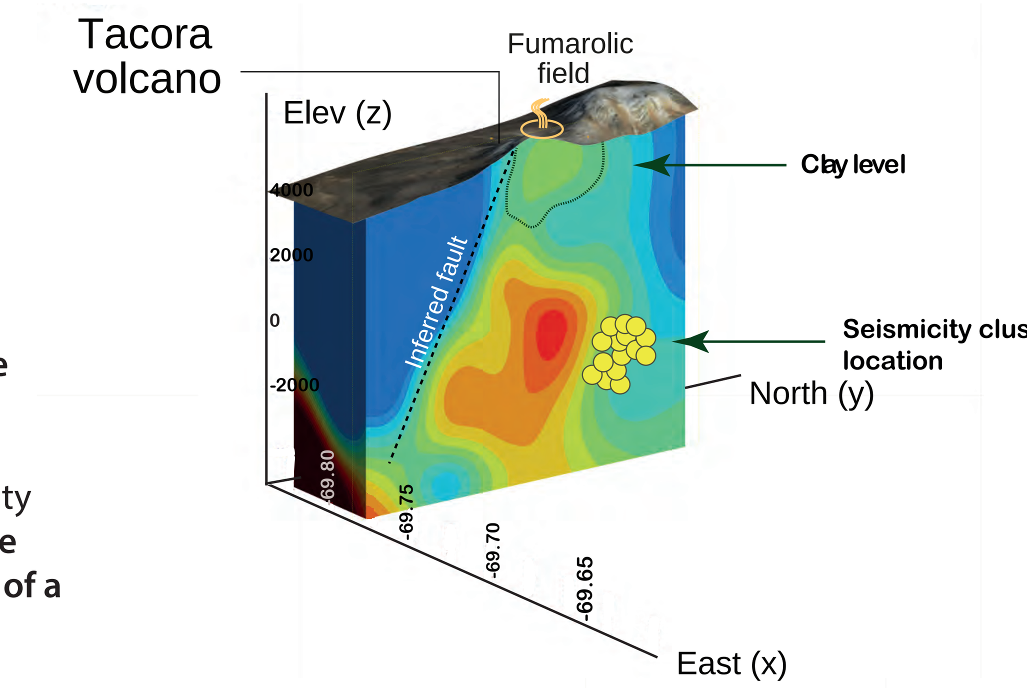
- **High Vp/Vs values (1.80 – 1.85)** located at the western sector of the area are interpreted as **fluid-saturated rocks.** The **origin of these fluids** is attributed to **glaciers** situated above ~5000 m a.s.l, **local precipitation** and **the proximity of La Yarada shallow aquifer.** The presence of liquid water is corroborated by low temperatures (82° - 93°C) recorded in the W fumarolic field (2) (Fig. 3).

- Orientation and vergence of the low velocity anomalies (Fig. 3 & 4) **suggest the presence of a high angle and locally blind structure** below the volcanic cover. According to the observed geometry we infer that this structure corresponds to the **Challaviento fault.** As there is no observable relation between local seismicity and the Challaviento fault (Fig. 2), **local seismic activity is likely related to brittle fracturing generated by fluid mobility,** or **with the emplacement and location of a magmatic reservoir** associated with Tacora volcano. Both, seismicity cluster and the proposed magmatic chamber are spatially correlated.

- The location and orientation of the **low Vp/Vs anomaly (Vp/Vs < 1.68)** and **low ΔVp/Vp (%)** next to the Challaviento fault **suggests the presence of a magmatic-hydrothermal reservoir** (Fig. 3 & 4) that governs the temperature range (270 – 310 °C) of the geothermal reservoir proposed by Capaccioni et al. (2011).

- According to our model, **yellow zones** (Fig. 3 & 4) could correspond to a **network of active channels.** These channels - **responsible for the circulation ofmagmatic – hydrothermal fluids** - can be supported considering the link betweenanomalies, surface manifestations, and the interpretative fluid circulation model presented by Capaccioni et al., (2011).

- The presence of this magmatic-hydrothermal reservoir gives rise to **clay levels** (3,5) (Fig. 4). These are identified with **intermediate Vp/Vs values** and **low ΔVp/Vp (%) values**. The existence of clay levels is also **strongly supported at the surface** by the presence of **hydrothermal alteration zones of argillic and advanced argillic type** in the volcanic edifice and the surrounding area (3). The forming conditions of these alterations corroborate **acid hydrothermal fluids near to 100°C**, which is coincident with the recorded temperatures in the NW fumarolic field (2).



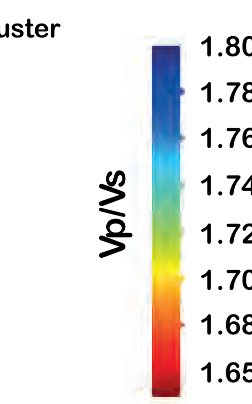
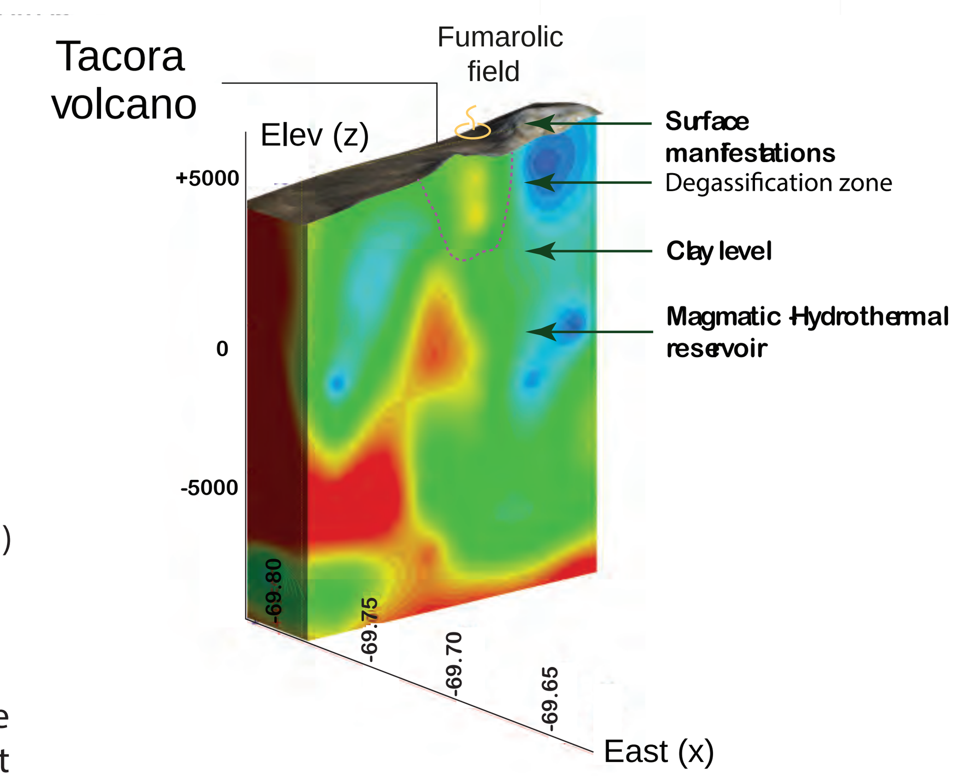


FIGURE 3

Cross section with a 2D projection of the final velocity model for Vp/Vs



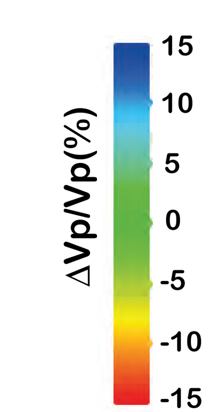


FIGURE 4

Cross section with 2D projections of the final velocity model for ΔVp/Vp (%)

E. CLUSTER ANALYSIS

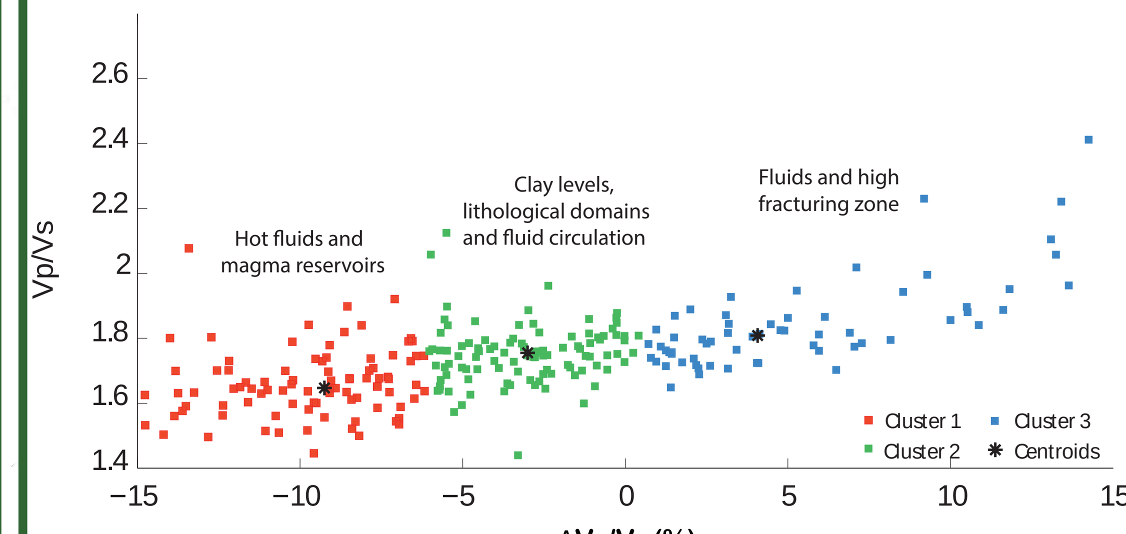


FIGURE 5

Clustering of Vp/Vs vs ΔVp/Vp (%) using k=3

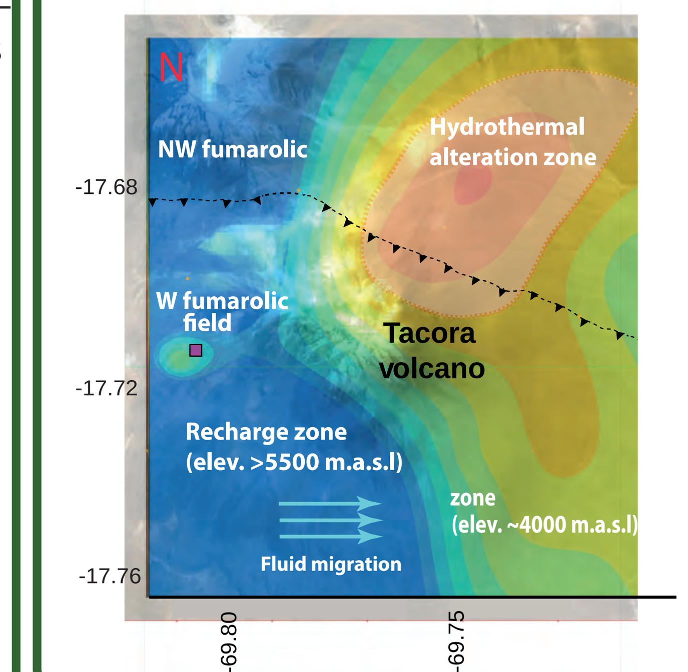
To better identify the phase segmentation that could be inferred from the Vp/Vs and ΔVp/Vp (%) models (Fig 3 & 4)**, a cluster analysis has been made. The clearly identifiable variations in ΔVp/Vp (%) represents stronger variations of the bulk modulus (κ) over the shear modulus (μ),** so gas or liquid phases can be identified. Based on this assumption, a ***k- means*** **clustering** function was used (Fig. 5). After testing, the selected number of clusters was **k=3.** In the first cluster, κ presents apercentage decline, indicating high temperatures and liquid or gaseous phases. Meanwhile, the third cluster groups a percentage increase suggesting low temperatures and solid phases. **Finally, the second cluster could be related to the location of clay caps, if and when it is followed by a decrease in the ΔVp/Vp (%) value, that is linked with a gas phase.** In our case, the decreasing in the ΔVp/Vp (%) value is observed and is directly related with a degassing zone -the NW fumarolic field-.

Therefore, the structure would allow us to identify clay levels inside the magmatic-hydrothermal systems is the next one, from depth to surface:

- a low ΔVp/Vp (%) value, linked with the hydrothermal-magmatic reservoir.
- an intermediate ΔVp/Vp (%) value linked with the clay level.
- a low and well located low ΔVp/Vp (%) related with a degasification zone.
- a fumarolic field type thermal manifestations on the surface.

F. MODEL OF FLUID CIRCULATION

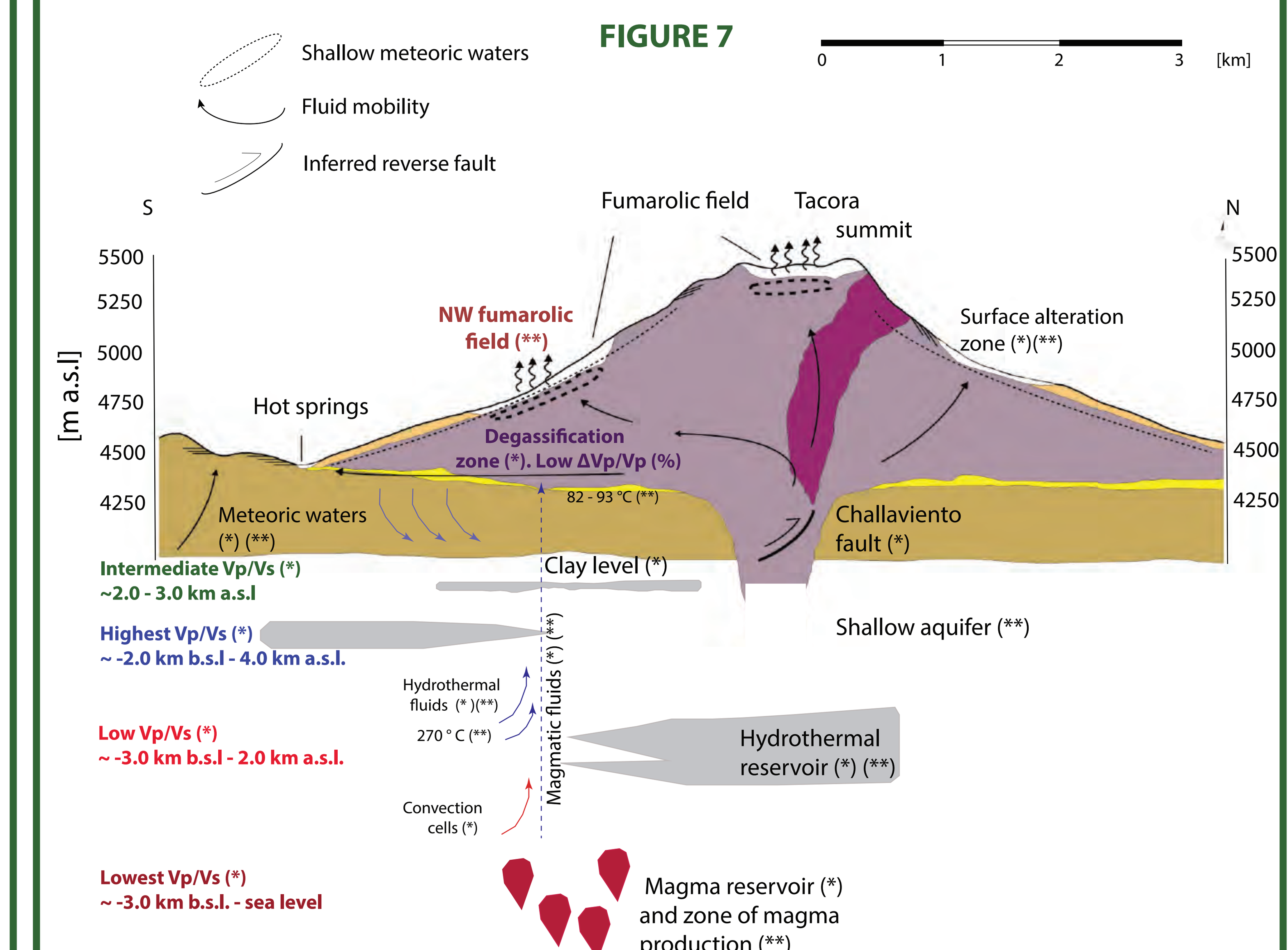
FIGURE 6



This model consists of an **overlap between topography, fumarolic fields location,** and the **first and shallow layer of the Vp/ Vs model** between **3.0 and 4.5 km a.s.l.)** (Fig. 6). **High Vp/Vs values** indicate the location of the **recharge zone of the magmatic – hydrothermal system. Topography** of the area, descending eastward (from ~5.500 to ~4.000 m.a.s.l.) **favors fluid migration**, which results in an area with **intermediate Vp/Vs values (1.68-1.74).** These fluids are part of the **hydrodynamic activity** of the system generating **convection cells** around **low velocity anomalies (Vp/Vs < 1.68).** Regarding the surface alterations, the low value anomaly located to the north-east, would be related to the **argillic alteration** previously observed in the zone.

G. CONCEPTUAL MODEL

FIGURE 7



Through the final velocity model, we developed an schematic model **based on geochemistry of fluid circulation and seismic tomography** (Fig. 7). This model enhance and support the results presented by Capaccioni et al. (2011): it was possible to **locate spatially** the **fault system** under the volcanic building, the **magmatic source**, a **NW clay level** and **the source of gases.** The results presented by Capaccioni et al. (2011) are marked with two asterisks (**). The results obtained in this research are shown with one asterisk (*). Common interpretations are marked with both symbols. As in many igneous systems in active volcanoes, the **magmatic-hydrothermal system can be represented with different Vp/Vs values**: a deep magmatic reservoir with the lowest Vp/Vs values; a hydrothermal reservoir with hot magmatic volatiles (low Vp/Vs); and a shallow aquifer with highest Vp/Vs values at the upper part of the system, given by the interaction between meteoric waters and magma volatiles. Clay minerals, formed in relation with the magmatic process, appears beneath the fumarolic field (intermediate Vp/Vs).

This research can be found in: ***Pavez, C., Comte, D., Gutierrez, F., Gaytan, D. 2019.Analysis of the magmatic-hydrothermal volcanic field of Tacora Volcano, northern Chile, using travel time tomography. Journal of South American Earth Sciences 94. 102247.***

Main references & software:

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