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# Volcano-Tectonic-Geothermal Domains on the Southern Andes Volcanic Zone

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## ABSTRACT

The interplay between tectonics and volcanism creates the conditions to form geothermal systems and controls the fluid chemistry evolution. The Southern Andes volcanic zone (SVZ) is one of the best natural laboratories to address such interplay because of the occurrence of numerous geothermal areas, recent seismic activity generated by regional fault systems, and intense volcanic activity. In this work, we integrate structural analysis at regional and local scale of active geothermal areas, with geochemical analysis of hydrothermal fluids, to define the development of magmatic-tectonic-hydrothermal domains. In the SVZ, volcanism is strongly controlled by the Liquiñe-Ofqui Fault System (LOFS), an intra-arc, strike-slip fault, and by the Andean Transverse Faults (ATF), a set of transpressive NW-striking faults. We identify two end-members on the magmatic-tectonic-hydrothermal domains. The Liquiñe–Ofqui fault system domain encompasses geothermal areas located either along the master or subsidiary faults. These are favorably orientated for shear and extension, respectively. In the LOFS domain, the geochemistry of hot spring discharges is controlled by interaction with the crystalline basement, and is characterized by low B/Cl. In marked contrast, the ATF domain includes geothermal occurrences located on the flanks of volcanoes forming WNW-trending alignments; these systems are built over faults that promote the development of crustal magma reservoirs. Unlike the first domain, the fluid chemistry of these geothermal discharges is strongly controlled by volcanic host rocks, and is typified by higher B/Cl ratios. Helium, nitrogen and carbon isotope signatures in hydrothermal fluids complements major and trace analyses results and enlighten on variation due to fault systems intersections and the northern termination of the LOFS. Results from this study provide new insights towards efficient exploration strategies of geothermal resources in Southern Chile.

## 1. INTRODUCTION

Geothermal activity is dependent upon the interaction between a heat source, circulating fluids, and permeable pathways. The conceptual models considering this interaction guide the exploration and exploitation of geothermal resources. The main inputs of the geothermal conceptual models are the permeability architecture and the fluid geochemistry (Goff and Janik 2000). The permeability architecture in geothermal systems is defined by the geometry and kinematics of fault–fracture networks (e.g. Sibson 1996). Faults may act as impermeable barriers to cross-fault flow or as high permeability conduits, although their permeability relative to the host rock depends on fault displacement, host rock lithology, hydrothermal mineral precipitation, and the seismic cycle. Fault–fracture networks including their damage zone damage zones are likely to develop directional permeability in the medium stress direction ($\sigma_2$) (e.g. Sibson 1996). During the past two decades, many studies about control of fault-fracture meshes on fluid flow have provided crucial information on how the local stress field controls fluid migration (Rowland and Sibson, 2004; Cox, 2010; Rowland and Simmons, 2012). Into this framework, the following fundamental questions arise: What are the primary controls of heat, fluid and metal transport in the crust? How does the volcano-tectonic setting impact the chemical and physical evolution of geothermal systems? Filling this knowledge gap is key to reveal the optimal geologic conditions leading to the development of high enthalpy geothermal resources.

An excellent natural laboratory to address those questions is the Andean Cordillera of Central-Southern Chile, where hydrothermal systems occur in close spatial relationship with active volcanism and regional fault systems. Tectonic activity is represented by two regional scale fault systems: the arc-parallel Liquiñe–Ofqui fault system (LOFS) and the WNW-striking and NE-striking arc-oblique andean transverse faults (ATF) (Cembrano and Lara, 2009; Perez-Flores et al., 2016; Stanton-Yonge et al., 2016; Sielfeld et al., 2019). Furthermore, these fault systems are genetically and spatially related to the magmatic evolution in the SVZ, forming two categories of volcano–tectonic associations (Cembrano and Lara 2009). (1) The LOFS, with NNE-striking master faults favorably orientated for dextral shear with respect to the prevailing stress field and NE-striking tension fractures likely to form under relatively low differential stress. Volcanic activity comprises NE-striking volcanic alignments containing mainly basaltic to basaltic–andesitic lithologies in either stratovolcanoes or minor eruptive centers. (2) The ATF with WNW-striking faults severely misorientated with respect to the prevailing stress field. The volcanic activity comprises WNW-striking alignments of stratovolcanoes and displays a more evolved magma series (basaltic to rhyolitic).

This article aims to (1) interpret the role of fault systems in geothermal fluid flow through a structural analysis of published field data (geometry and kinematics) and (2) establish the processes that define the chemical evolution of fluids through analyses of major and trace elements and isotopic composition of geothermal fluids (water and gas). The details on the methods used are presented in Sánchez et al., (2013), Perez-Flores et al., (2016), Tardani et al., (2016) and Wrage et al., (2017). Our results show the occurrence of two distinctive magmatic-tectonic-geothermal domains, which define the heating mechanism and chemical evolution of geothermal fluids in the SVZ.

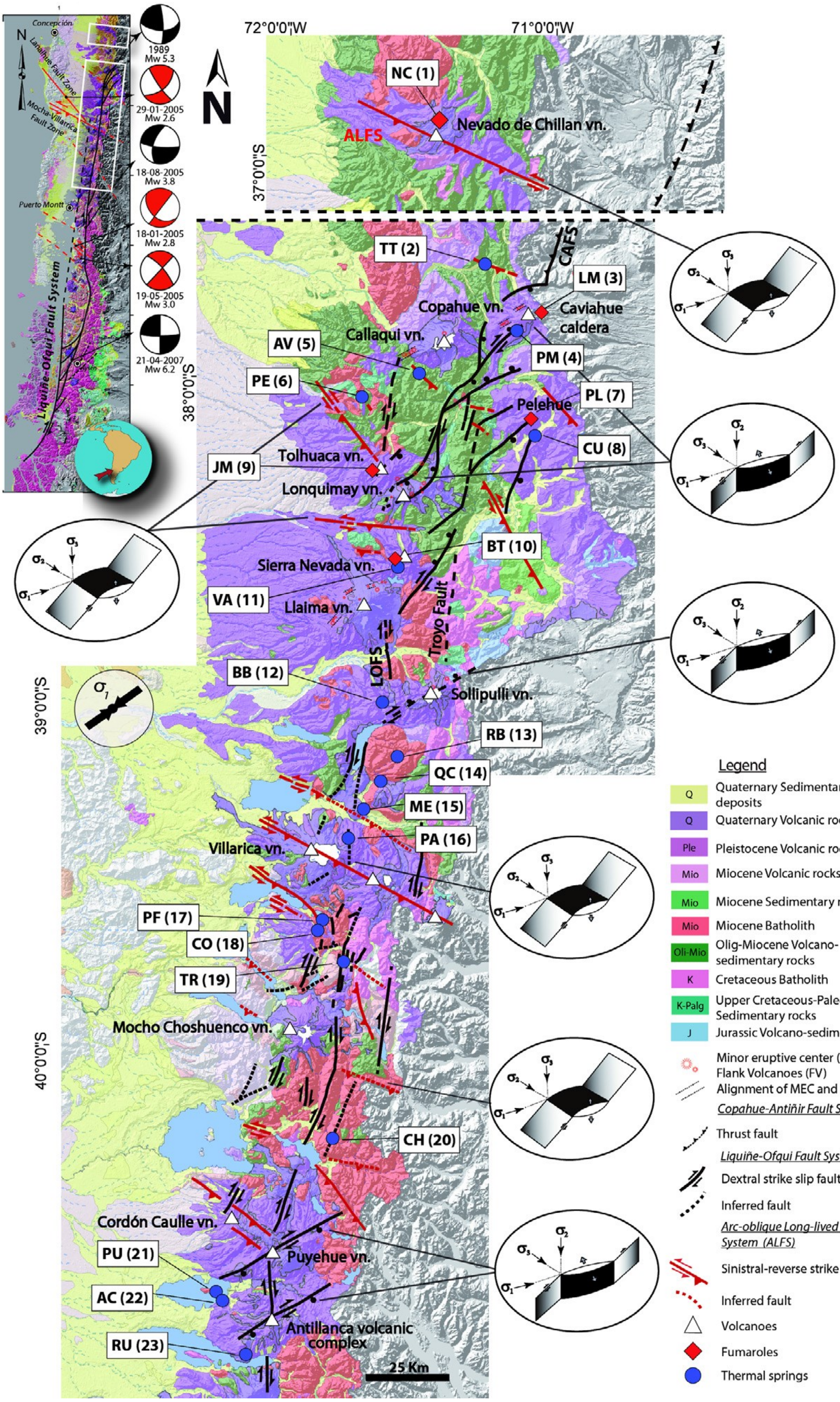


**Figure 1: Geologic and structural map of the central part the Southern Volcanic Zone (SVZ) in southern Chile from Tardani et al., 2017. Solid and dashed lines represent main and secondary faults from Perez-Flores et al. (2016). Blue circles and red diamonds represent the location of thermal springs and fumaroles samples, respectively. White triangles represent the main stratovolcanoes of the region. Sigma 1 ($\sigma_1$) represent the maximum regional stress field. CAFS: Copahue-Antinir Fault System, LOFS: Liquine-Ofqui Fault System, ALFS: ATF, Andean Transverse Faults. Stress fields for the distinct fault segments are modified from Sanchez et al. (2013) and Perez-Flores et al. (2016).**

## 2. RESULTS AND DISCUSION

### 2.1 Fault-slip data

A detailed structural mapping was performed in order to characterize the geometry, kinematics and timing of deformation on structural domains of the LOFS and ATF in the northern termination of the LOFS (see Perez-Flores et al., 2016 for details).. Within these areas, seven key structural sites were identified, which are representative of LOFS and ATF fault zones. Collected structural data include description, measurement and logging of the geometry, kinematics, texture, mineralogy and crosscutting relationship of different structural elements (i.e. fault veins, veins, hydrothermal breccias). Structural data collected was analyzed from regional and local scales. The regional scale was defined by the inversion of the entered fault-slip data collected at the study area, whereas for local scale the inversion is the results of fault-slip data of each structural site. Two different softwares were used to determine the strain and stress axes, Faultkin and Multiple Inversion Method (Perez-Flores et al., 2016).

Fault-slip data analysis yields stress and strain fields from the full study area data base (regional scale) and fault zones representative of each fault system (local scale). Regional scale strain analysis shows kinematically heterogeneous faulting. Local strain analyses indicate homogeneous deformation with NE-trending shortening and NW-trending extension at NNE-striking Liquiñe–Ofqui master fault zones. Strain axes are clockwise rotated at second order fault zones, with ENE-trending shortening and NNW-trending stretching. The ATF record polyphasic deformation. Conversely, stress field analysis at regional scale indicates a strike-slip dominated transpressional regime with N64°E-trending $\sigma_1$ and N30°W-trending $\sigma_3$. The regional tectonic regime controls the geometry of NE-striking dikes and volcanic centers. NE-striking faults record local stress axes that are clockwise rotated with respect to the regional stress field. NNE- and NE-striking faults are favorably oriented for reactivation under the regional stress field and show poorly-developed damage zones. Conversely, NW-striking fault systems, misoriented under the regional stress field, show multiple fault cores, wider damage zones and dense vein networks.

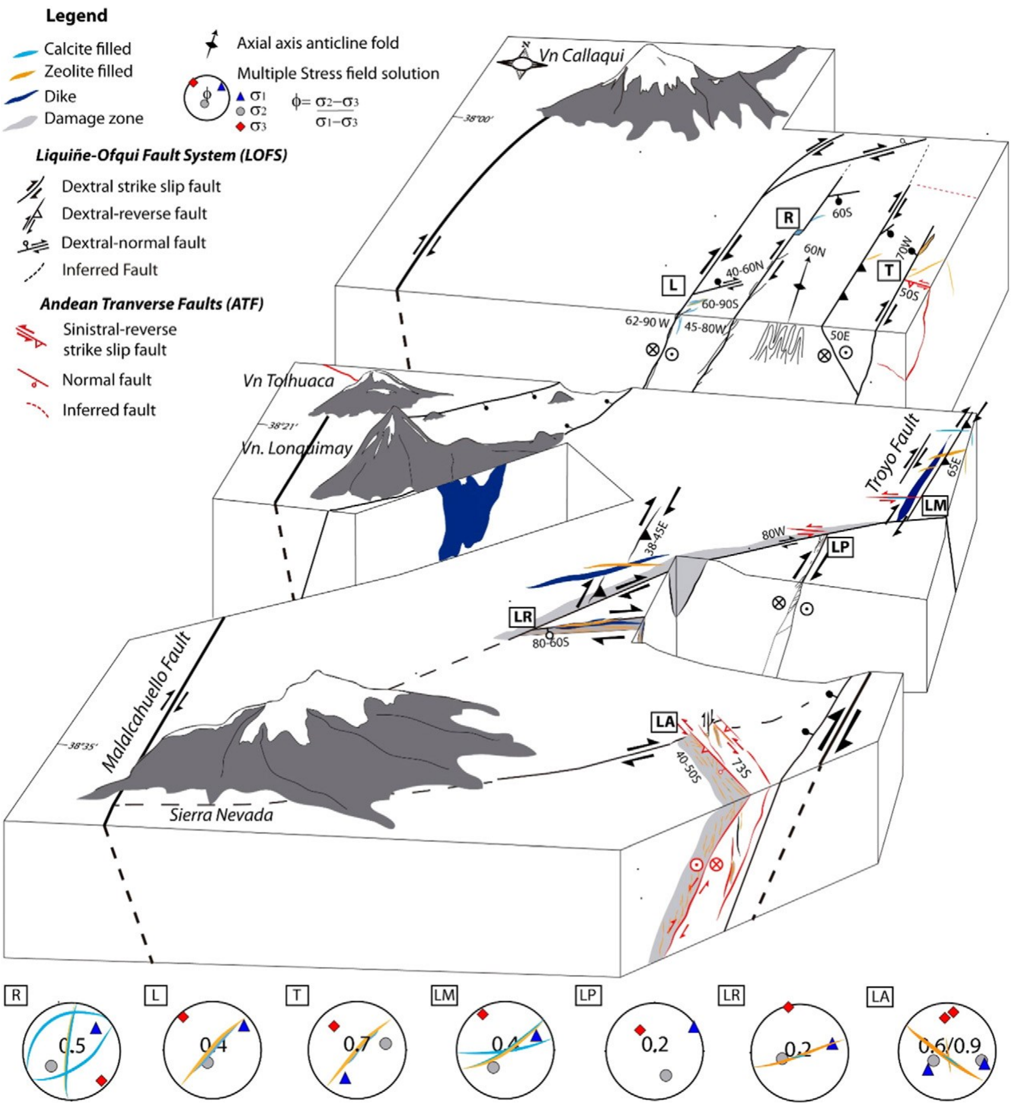


**Figure 2: Schematic block diagram illustrating the geometrical arrangement and kinematics of faults and other structural elements at the northern termination of the LOFS (black lines) together with the main traces of the ATF (red lines), taken from Perez-Flores et al., 2016. The cartoon shows the local stress field solutions and the veins main orientation at the different structural sites (R: Ralco, L: Lolco, T: Troyo, LP: La Poza, LM: Las Mentas, LR: Las Raices, LA: Las Animas).**

To assess the interplay of volcano–tectonic associations and geothermal systems we define two magmatic-tectonic geothermal domains: the LOFS domain and the ATF domain (Sanchez et al., 2013). The LOFS domain includes geothermal areas located along either master or subsidiary faults of the LOFS. There, thermal water emerges mainly from fractures in granitoids or sediments overlying them. Main structural features of this domain are the arc-parallel NNE-striking dextral strike–slip master faults and subsidiary NE-striking dextral and normal faults which are favorably oriented for shear and/or extension with respect to the prevailing stress field. Volcanic systems linked to these faults exhibit primitive magmas, which are transported through tension cracks with no magmatic chamber development (Cembrano and Lara 2009). The ATF domain hosts geothermal areas, which are located on the WNW-trending aligned volcano flanks where hot springs discharge from volcanic rocks or sedimentary deposits overlying them. The condition for reactivate faults of ALFS promotes long residence of magma in crustal reservoirs, which may serve as heat sources for geothermal systems.

Most of the geothermal areas with thermal features are spatially associated with regional fault systems, and the hot spring alignments exhibit a similar trend. This is consistent with the idea of a first order control exerted by brittle deformation on hydrothermal fluid flow once the initial porosity is destroyed by hydrothermal alteration (e.g. Cox 2010; Rowland and Sibson 2004; Rowland and Simmons 2012). Thus, the secondary architecture permeability overprints the intrinsic permeability anisotropies originated by stratification in porous rocks. Fault–fracture networks, consisting of faults, extensional fractures, and extensional shear-fractures are conduits for hydrothermal fluid flow. Activation and preservation of fault–fracture networks as highly permeable conduits require the condition of fluid pressure $P_f \sim \sigma_3$ (Sibson 1996). In these networks, the directional permeability follows a direction parallel to σ2, which is perpendicular to the slip vector (Sibson 1996). Therefore, in the damage zone of the strike–slip LOFS domain ($\sigma_1 \sim$N60E; Lavenu and Cembrano 1999), the vertical permeability is enhanced. These are the ideal conditions to form a deep convection cell. However, in the ATF domain the permeability is only enhanced under fluid overpressure conditions, i.e. when fluid pressure ($P_f$) is higher than lithostatic pressure. When this condition is met, fault–fracture networks mainly promote lateral circulation of fluids. At shallow levels (<2 km) and hydrostatic conditions, it is more likely to activate tension fractures or shear fractures instead of misorientated faults (Rowland and Simmons 2012). That is the case of geothermal fluids at shallow levels in both domains, transported through ENE-tension fractures as reflected by ENE-aligned hot springs. The recharge of the systems with meteoric water is also likely to occur through ENE-tension fractures of fault–fracture networks.

### 2.2 Thermal waters chemistry

Thermal waters in the Southern Volcanic Zone (SVZ) of Chile were studied using major and selected trace element relationships to characterize their geochemistry, formation mechanisms, and to explore the influence of regional structural controls on fluid composition (see Wrage et al., 2017 for details). Three sets of waters were identified based on physicochemical characteristics: (i) NaCl waters, (ii) acid-sulfate waters, and (iii) bicarbonate ($HCO_3$) waters. NaCl waters are the most abundant type in the studied region and their chemistry is controlled by significant water-rock interaction (Wrage et al., 2017). They are characterized by an alkaline pH (7.2–9.3), generally lower temperatures (avg: 55 °C), and relatively high concentrations of Cl, Na, B, As, Li, and Cs. Acid-sulfate waters are typically associated with volcanoes and have a strong magmatic/volcanic component due to the absorption of magmatic vapors. They are acidic (pH < 4), generally higher in temperature (avg: 85 °C), and have elevated concentrations of $SO_4$, Mg, and Ba. Bicarbonate waters are characterized by the highest concentrations of $HCO_3$ (> 892 ppm) in the region and are similar in temperature (< 47 °C) and pH (> 6.2) to NaCl waters. They have elevated concentrations of most cations (Ca, K, Na, Mg, Ba, Sr) as a result of intense shallow cation leaching due to the absorption of $CO_2$-rich volcanic vapors on the peripheries of geothermal systems. The thermal waters were also characterized according to their spatial relation with the dominant fault systems of the region: the NNE-striking intra-arc LOFS and the WNW-striking ATF. The inherent differences in fault nature between these fault systems constitutes the primary structural control influencing geothermal fluid development in the SVZ. The chemistry of waters spatially associated with the LOFS as a whole is defined by high vertical permeability networks and lack magmatic reservoir development. Therefore, these waters tend to have higher Cl/B ratios and strong correlations between trace alkali metals and Cl due to rapid, efficient upflow pathways. In contrast, waters spatially associated with the ATF have lower Cl/B ratios and show no correlation between trace alkali metals and Cl due to degassing magma chambers and decreased vertical permeability. The relationship between water type and structural domain in Cl/B ratios and trace metal behavior provides evidence that fault geometry and kinematics exert a fundamental control on geothermal fluid development in the SVZ of Chile.

### 2.3 Helium, nitrogen and carbon isotope signatures

Helium, carbon and nitrogen isotope data ($^3He/^4He$, $\delta^{13}C$–$CO_2$ and $\delta^{15}N$) of a suite of fumarole and hot spring gas samples from 23 volcanic/geothermal localities that are spatially associated with either the LOFS or the ATF in the central part of the SVZ have been studied (see Tardani et al., 2017 for details). The results are characterized by a wide range of $^3He/^4He$ ratios (3.39 Ra to 7.53 Ra, where Ra = (($^3He/^4He$)air), $\delta^{13}C$–$CO_2$ values (-7.44‰ to -49.41‰) and $\delta^{15}N$ values (0.02 ‰ to 4.93‰). The regional variations in 3He/4He, $\delta^{13}C$–$CO_2$ and $\delta^{15}N$ values are remarkably consistent with those reported for $^{87}Sr/^{86}Sr$ in lavas along the studied segment, which are strongly controlled by the regional spatial distribution of faults. Two fumaroles gas samples associated with the northern ‘‘horsetail” transtensional termination of the LOFS are the only datapoints showing uncontaminated MORB-like $^3He/^4He$ signatures. In contrast, the dominant mechanism controlling helium isotope ratios of hydrothermal systems towards the south appears to be the mixing between mantle-derived helium and a radiogenic component derived from, e.g., magmatic assimilation of $^4He$ -rich country rocks or contamination during the passage of the fluids through the upper crust. The degree of $^4He$ contamination is strictly related with the faults controlling the occurrence of volcanic and geothermal systems, with the most contaminated values associated with NW-striking structures. This is confirmed by $\delta^{15}N$ values that show increased mixing with crustal sediments and meteoric waters along NW faults (ATF), while $\delta^{13}C$–$CO_2$ data are indicative of cooling and mixing driving calcite precipitation due to increased residence times along such structures. Our results show that the structural setting of the region exerts a fist-order control on hydrothermal fluid composition by conditioning residence times of magmas and thus promoting cooling/mixing of magmatic vapor, and therefore, must be taken into consideration for further geochemical interpretations.

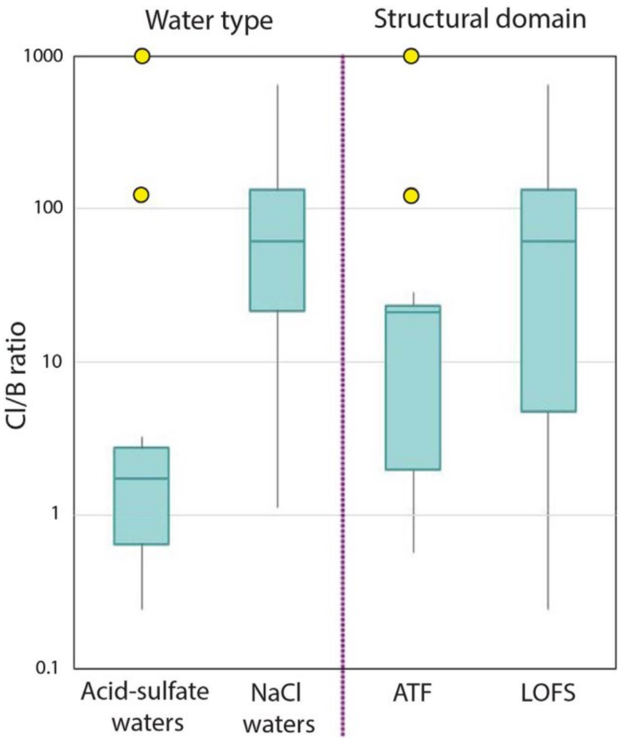


**Figure 2: Box plot of Cl/B ratios in thermal waters, compared according to water type (acid-sulfate vs NaCl waters, a) and fault domain (LOFS vs ATF, b). The two outliers for acid-sulfate and ATF waters in yellow circles.**

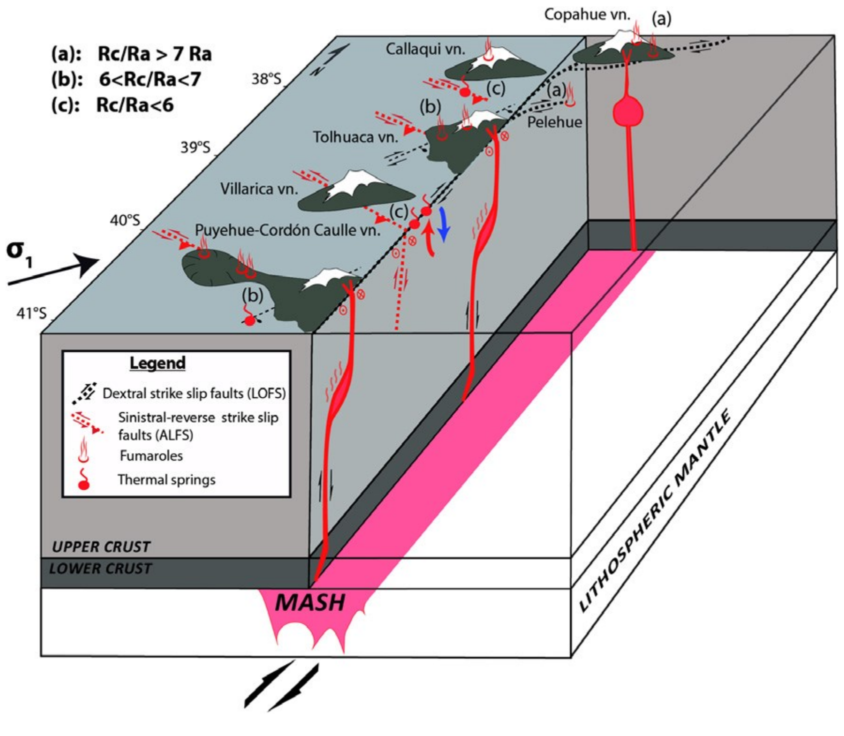


**Figure 2: Block model showing the structurally-controlled fluid circulation model proposed for the studied segment of the Southern Volcanic Zone, taken from Tardani et al., 2017. Black and red dashed lines represent the LOFS and ATF, respectively. Fumaroles and hot springs are represented along with their relation to volcanic edifices and structural settings. In (a) fumaroles and hot springs show MORB-like $^3He/^4He$ ratios indicating primitive sources and no significant degrees of crustal contamination at the norther termination of the LOFS. In (b) thermal features are spatially associated with stratovolcanoes controlled by transtensional NE-striking faults (e.g., Sollipulli volcano; Fig. 1) or by the intersection between NE-(LOFS) and NW-striking transpressive faults (ATF) (e.g., Tolhuaca and Cordon Caulle volcanoes. In (c) thermal features are associated with stratovolcanoes that are controlled by pure transpressive NW-striking faults (Nevado de Chillan, Villarica and Mocho-Choshuenco volcanoes) and also the cases unrelated to volcanism (Chihuio, Trafipan) presenting the highest degrees of crustal contamination. Blue and red arrows represent the mixing between deep and meteoric fluids. Sigma 1 ($\sigma_1$) represent the maximum regional stress field.**

## 2. CONCLUSION

We have identified two magmatic-tectonic-geothermal domains based on the nature and kinematics of fault systems, volcanic activity, and rock types: the ATF domain and the LOFS domain. The chemistry of the fluids shows contrasting signatures in these domains in major and trace elements and in helium, nitrogen and carbon isotopes. We propose that the role of fault systems on the geochemical evolution of geothermal fluids occurs through the development of magmatic-tectonic-geothermal domains, which ultimately defines the heat source.

● In the LOFS domain, fault–fracture networks related to the damage zone of the deep seated NNE-striking master fault increases vertical permeability in the crystalline basement. These fracture networks promote development of deep (<3 km) convection cells and heat–fluid–rock interaction after the infiltration of meteoric water. The ultimate heat transfer mechanism of fluids is by conduction from the crystalline host rock in the high heat flow realm of the intra-arc. The heat–fluid–rock interaction and the lack of direct magmatic contribution imprints a signature of low B/Cl ratios and high pH in the composition of the geothermal fluids. The hot springs discharge from the faulted crystalline basement. However, a deep contribution of mantle-derived He is not null even in this domain revealed by values of $^{3}He/^{4}He$ considerable higher than the pure crustal $^{3}He/^{4}He$ signature of 0.02 Ra.

● In the ATF domain, the WNW-striking inherited basement faults, which are strongly disorientated with respect to the prevailing stress field, provide suitable conditions for the development of magma reservoirs. These crustal magmatic reservoirs are the source of heat and mass for the geothermal systems. The mass transfer results in a signature of higher B/Cl ratios and neutral pH in the chemistry of the geothermal fluids compared to those of the LOFS domain. Therefore, the geochemical evolution in the ATF domain can be represented as meteoric water absorption of magmatic gases, interaction with volcanic rocks, and dilution. The discharge of these systems is through volcanic units, which may promote lateral fluid flow. Exploration should be focused on this domain that is likely to promote the development of the most prominent geothermal resources.

● At shallow levels (<2 km) under hydrostatic conditions, the fluid flow is though NE-tension fractures optimally orientated for reactivation where discharge (hot springs) and recharge (meteoric waters) of fluids in the geothermal systems is likely to occur.

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