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The Nevados de Chillán as a fault-controlled Geothermal System in Southern Chile: a review of the last achievements to a new conceptual model

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1 INTRODUCTION

Geothermal systems hosted in crystalline rocks with low primary permeability represent a promising yet complex target for sustainable energy development. In these systems, heat is extracted from the circulation of fluids within fractured and low-porosity rock matrix, where permeability is primarily controlled by fault and fracture networks rather than matrix properties (e.g., Siratovich et al., 2014; Jolie et al., 2021). Understanding how fluids migrate through these complex structures is essential for successfully exploring and exploiting geothermal resources in fractured reservoirs. Moreover, a robust understanding of how hot geothermal fluids could flow throughout these crystalline fractured low-permeability rocks implies several assumptions when mostly available data from the surface are available. The Nevados de Chillán Volcanic Complex (NChVC), located in the Southern Volcanic Zone (SVZ) of the Andes (Figure 1a), is selected as a representative case study of Andean geothermal systems hosted in a crystalline fractured reservoir. Its unique combination of active volcanism, a well-developed fracture system, and associated geothermal manifestations (e.g., Morata et al., 2023; López-Contreras et al., 2025; Mura et al., 2025) makes it a world-class site for improving our understanding of fluid flow in fractured geothermal systems hosted in crystalline rocks. In this sense, during the last five years, our research group has focused on the studies of this active geothermal system from a multidisciplinary approach. Combining mineralogical, geochemical, structural, and geophysical methods, and numerical modeling, we have developed an updated conceptual model for the Nevados de Chillán Geothermal System (NChGS).

2 GEOLOGICAL SETTING

The NChGS is located on the SW border of the active NChVC (Figure 1b). The basement of the volcanic complex includes Miocene granitoids of the Santa Gertrudis-Bullileo batholith, Miocene volcano-sedimentary sequences of the Cura-Mallín Formation, Miocene aureole of contact metamorphism denominated Hornfels Unit, and volcanic sequences of the Cola de Zorro Formation of Pliocene and Pleistocene age (Figure 1b). Since the Upper Pleistocene, the activity of the NChVC has been concentrated in two subcomplexes: Cerro Blanco in the northwest and Las Termas in the southeast (Figure 1b). Since then, volcanic activity has apparently been controlled by the presence of the Arc Transverse Fault System (ATF) (e.g. Cembrano and Lara, 2009) with stratovolcanoes developing aligned along the NW-SE trending Nevados de Chillán Lineament (Figure 1b). This structure plays a fundamental role in the intersections with structures formed by the present-day convergence, which could favor the generation of large reservoirs of magmatic and hydrothermal fluids. In this sense, present-day seismic activity suggests the existence of volcano-tectonic event sources aligned with this NW-SE trending structure (e.g., Cardona et al., 2021; Morata et al., 2023).

Most relevant surface thermal manifestations of the NChGS are located in the Las Termas-Olla de Mote and Aguas Calientes sectors (Figure 1b). This geothermal system was initially explored at the end of the ‘90s by the French Geothermal National Company, and a continuous 1000.85 m depth exploration well (Nieblas-1, see

location on Figure 1) was drilled in 2009 by the Chilean National Geothermal Company. A high-enthalpy reservoir was proposed to be hosted in intensely fractured Miocene granitic rocks, where temperatures could reach up to 250° C at 1200–1300 m depths. In contrast, a clay cap of ~600 m thick is developed in volcanic overlying sequences, and surface thermal manifestations (fumaroles, thermal and mud springs, etc.) are strongly fault-controlled (Morata et al., 2023; López-Contreras et al., 2025).

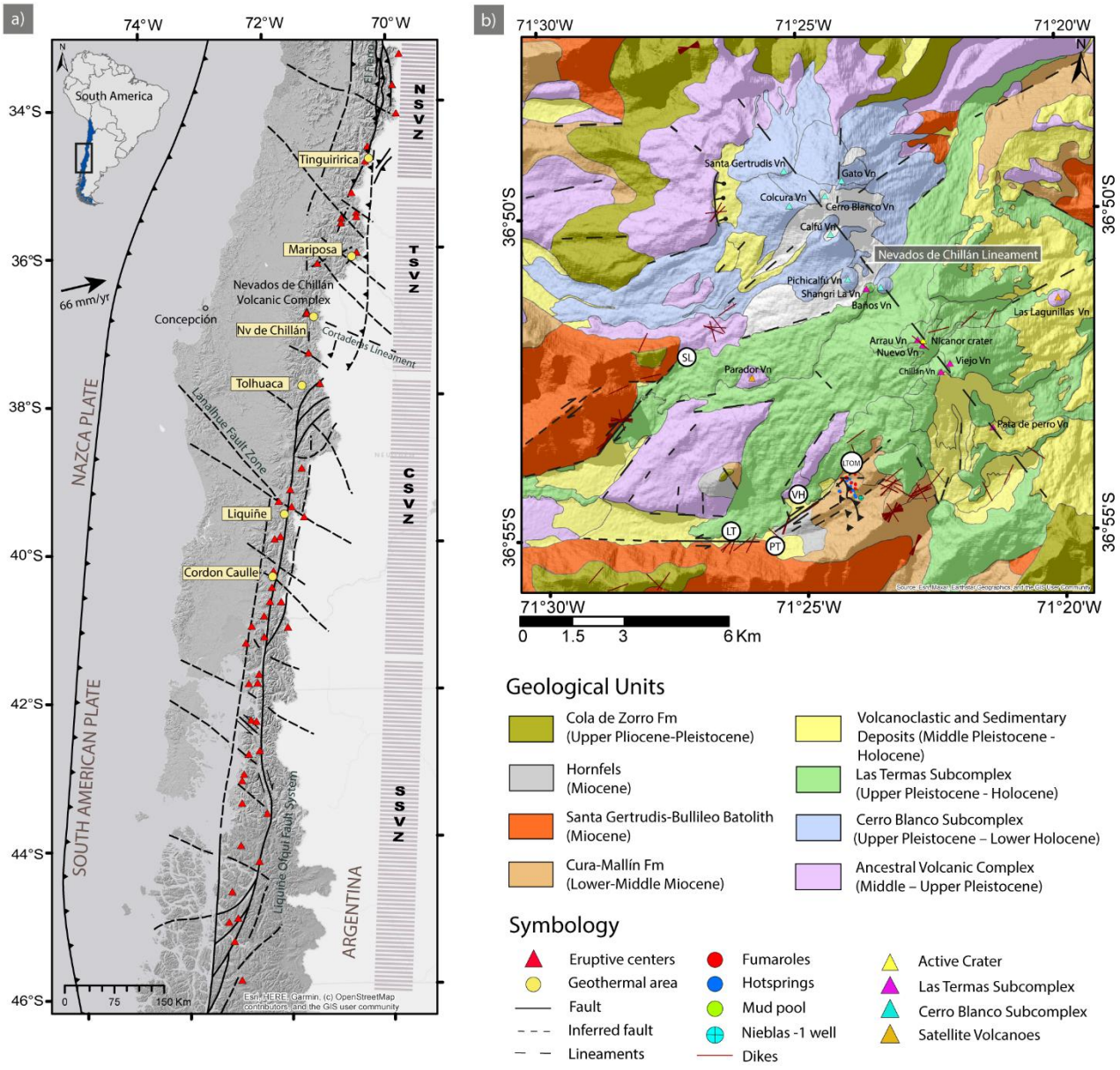


Figure 1: a) Main structures in the Andean Southern Volcanic Zone (SVZ) with the major geothermal areas taken from Morata et al. (2023). NSVZ: Northern Southern Volcanic Zone; TSVZ: Transitional Southern Volcanic Zone; CSVZ: Central Southern Volcanic Zone; SSVZ: South Southern Volcanic Zone. b) Geology of the Nevados de Chillán Volcanic Complex (NChVC) from Mura et al (2025).

3 STRUCTURAL CONTROL OF FLUID-FLOW PATHWAYS

A recent paper by Mura et al. (2025) summarizes our main results concerning the structural control of fluid-flow pathways in the NChGS. Major structural features include high-angle E-W, ENE, and WNW sinistral transcurrent faults in Las Trancas (LT), with secondary populations of NE and NNE dextral faults in Valle Hermoso (VH) and Shangri-La (SL) sectors (see Figure 1b). Additionally, low-angle thrust faults parallel to the Cura-Mallín Formation stratification are evident in the Las Termas - Olla de Mote area (LTOM). Fracture patterns exhibit varying orientations across different rock units, with NNE-SSW, NE-SW, and NNW-SSE orientations predominant in the crystalline units. Additionally, WNW and NW sets prevail in the younger overlying volcanic units. The most

suitable distribution fit for the length of fractures is a power law with exponent ~3, indicating that longer fractures are relatively less abundant than shorter ones.

Compared with seismic data, inversion of fault-slip data suggests a transtensional regime with subhorizontal NE-trending σ1. The fault-fracture network, formed by different stress regimes and cumulative strain throughout the area's geological history, interacts with the present-day stress field, playing a key role in fluid flow and geothermal processes. Fractures and faults aligned with the local present-day maximum horizontal stress axis exhibit high dilation tendencies and, hence, are likely to exert significant control over fluid circulation in the area.

In NChGS, the NE and E-W high-angle strike-slip faults could be primary conduits facilitating the upward migration of hot fluids from reservoirs within crystalline and fractured rocks such as the hornfels and intrusive rocks of the Santa Gertrudis-Bullileo Batholith. Furthermore, the orientations of other structures (NNW and NW) also play a crucial role in the overall connectivity – and therefore bulk permeability – of the fracture pattern, particularly in the intersections and interactions between fault and fracture networks.

4 CONCEPTUAL MODEL

Based on a multiscale approach, the multidisciplinary work performed in the NChGS during the last five years allows us to propose a conceptual model for this active geothermal system. The interpretation of surface geothermal manifestations coupled with detailed mineralogical studies from samples of the Nieblas-1 exploration well, together with inversion of fault-slip data, combined with seismic observations, suggests that the fault-fracture network, shaped by multiple stress regimes and cumulative strain over the area's geological history, interacts with the present-day stress field and plays a key role in fluid flow and geothermal processes. The major structural features identified include high-angle E–W, ENE, and WNW sinistral strike-slip faults identified in the granodioritic rocks of the Santa Gertrudis-Bullileo Batholith, with the main fault trace referred to as the Las Trancas Fault (Figure 1b). Secondary fault populations consist of NE- and NNE-trending dextral faults affecting hornfels in Valle Hermoso and dioritic rocks in Shangri-La, with their principal traces named after each respective zone. Furthermore, low-angle thrust faults parallel to the Cura-Mallín Formation stratification are identified in the Las Termas - Olla de Mote area, where the most intense surface thermal manifestations are present (López-Contreras et al., 2025) acting as a clay cap of the system. Structures aligned with the current maximum horizontal stress axis (trending NE) and high dilation tendencies, act like conduits for the ascent of fluids from the deeper fractured reservoir towards the most superficial levels. The surficial NNW-striking low-angle faults and lithological changes affect local permeability of altered volcaniclastic rocks that divert fluid circulation towards the surface. Then, both fault-fracture network and lithological factors constrain the heterogeneous distribution of geothermal alteration on the surface (López-Contreras et al., 2025).

Finally, our numerical models suggest hydrothermal fluid residence times of a thousand years are required to reach a steady-state thermal configuration (Oyarzo-Céspedes et al., 2025). In this model, the parameter that mainly controls the behavior of the isotherms is the permeability, which is directly related to the heat transport mechanism in each of the zones. The permeability in the reservoir was modeled as multiple compound fault zones, according to the permeability distribution suggested by Faulkner et al., (2010). For permeabilities lower than 10^{-16} m^2 heat tends to be transferred conductively, whereas at permeabilities higher than 10^{-14} m^2 heat tends to be transferred in a convective regime. The model clearly suggests the presence of a geothermal reservoir in the zone of convective behavior of the isotherms, where granodioritic rocks are highly fractured.

Considering all parameters obtained during this research project, using a volumetric method approach and the implementation of a single flash plant, it is possible to estimate an electric power generation potential of 39 ± 1 MWe with 90 % confidence level. This value agrees and is within the same range of magnitude evaluated in previous works (e.g. Aravena et al., 2016).

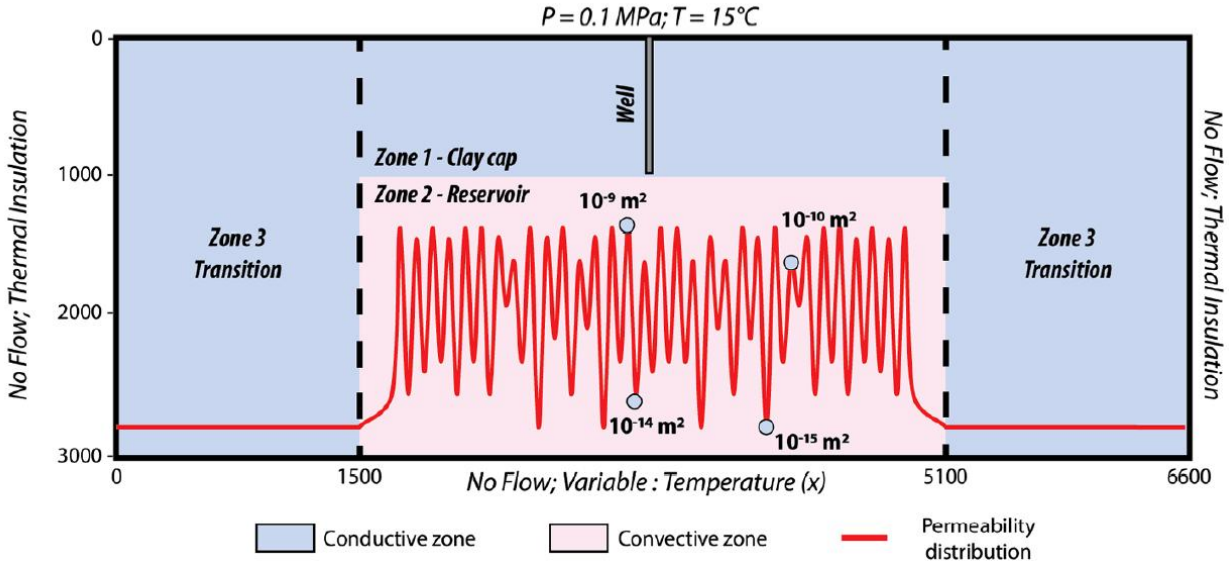


Figure 2. Boundary conditions with the expected distribution of conductive (Zones 1 and 3) or convective (Zone 2) behavior for numerical modeling of NChGS (West-East profile centered on the one-kilometer-deep well, scale is in meters). In the reservoir zone, the variable permeability distribution was adjusted to a highly fractured medium like multiple compound fault zones (from Oyarzo-Céspedes et al., 2025).

5 CONCLUSIONS

Our detailed mineralogical, structural, and numerical modeling of the NChGS reveals a complex network by the intersection of faults and fractures. This fracture network within crystalline rocks predominantly governs the underlying geothermal system, and its connectivity enhances fluid flow. These insights deepen our understanding of the geothermal dynamics in this region and highlight the potential for optimizing geothermal energy extraction. Although today, NChGS is an abandoned project by the former private owner company, the electricity demand for the Nevados de Chillán ski resort and the surrounding touristic Las Trancas Valley, coupled with a more diverse direct use rather than limited thermal spas, could be an economic incentive for a sustainable development of this geothermal system. Future research should focus on detailed modeling of fluid flow within these structures to further enhance our knowledge and quantify the potential yield from the geothermal resource.

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